

Introduction to Microwave Atomic Clocks

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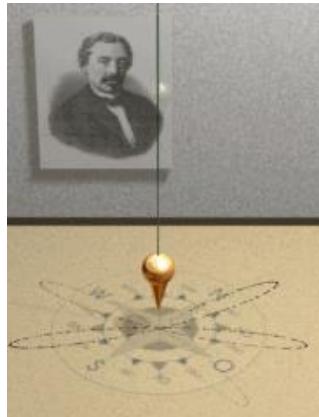
Tutorial Overview

- What is a clock?
 - How good are they?
- What is an Atomic Clock?
- Stable vs. Accurate
- Commercial vs. Laboratory
- Microwave vs. Optical
- Microwave clock examples in detail
 - Cesium Beam, Maser, Rubidium, Fountain, Trapped Ion
- Applications
 - Navigation/GPS, Time Stamping, Space, Fundamental Physics

What are the fundamental components of a clock?

Clock Schematic

Everything is an Oscillator (*but some things make better clocks*)



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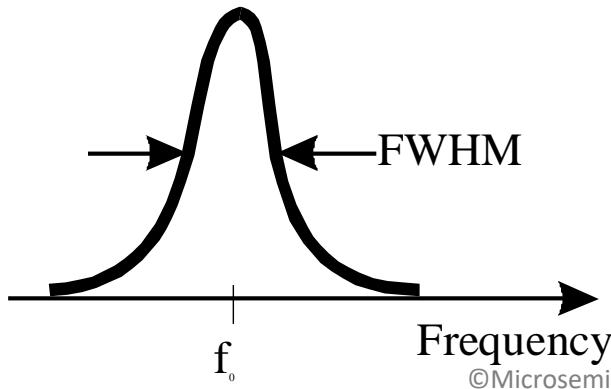
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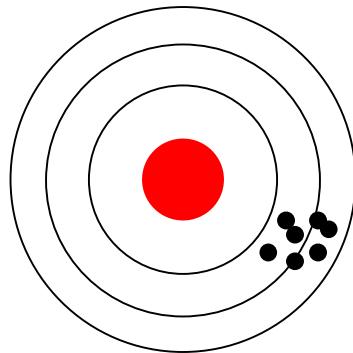
(Oscillator + Counter = Clock)



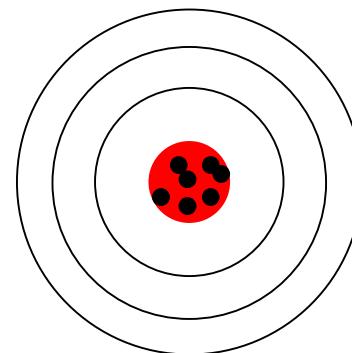
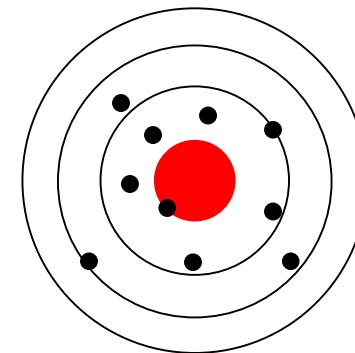
$$Q = \frac{\text{Resonant Frequency}}{\text{linewidth (FWHM)}} = \frac{\text{Ring-down Time}}{\text{Period}}$$

Precision vs. Accuracy

Stable or Precise, but not accurate



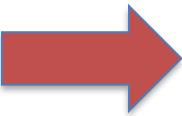
Accurate, but not precise



Accurate and precise

How Do We Characterize Clock Performance?

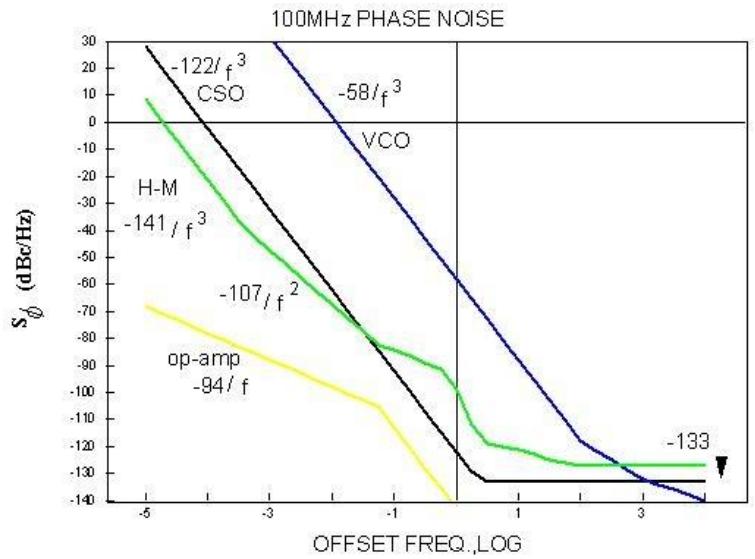
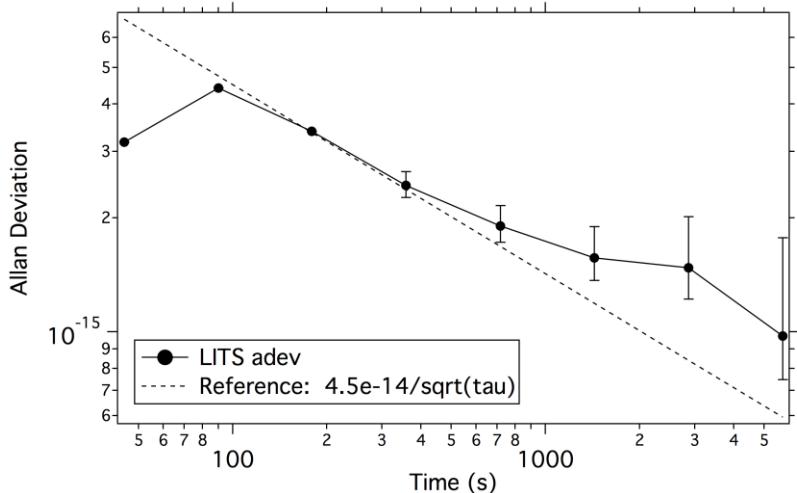
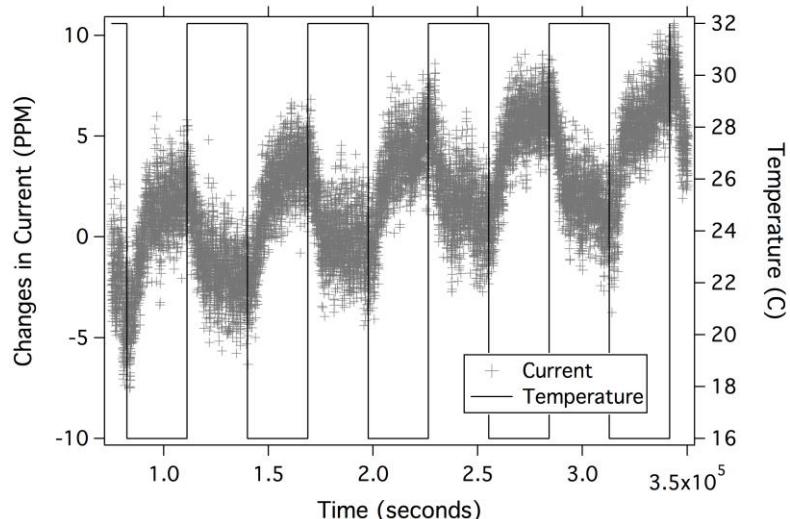
Time domain: Allan deviation



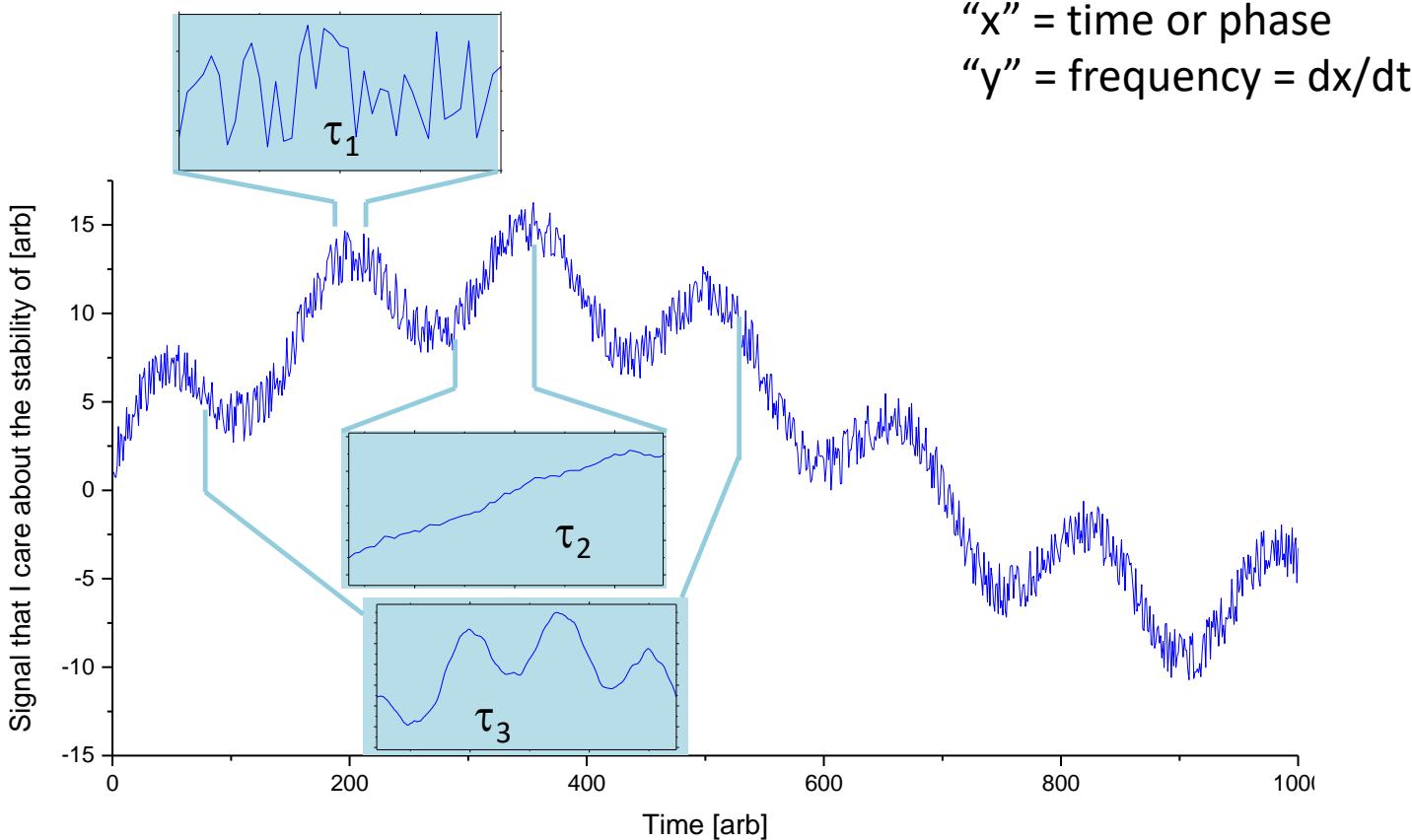
Frequency domain: phase noise (oscillators)

Systematic Sensitivities

- electromagnetic
- thermal
- barometric



How to Interpret the Allan Deviation



Allan Deviation, $\sigma_y(\tau)$ is RMS of x at averaging time, τ :

$$\sigma_{audev}(\tau) = \sqrt{\frac{1}{2(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2} \quad y_i = \frac{x_{i+1} - x_i}{\tau}$$

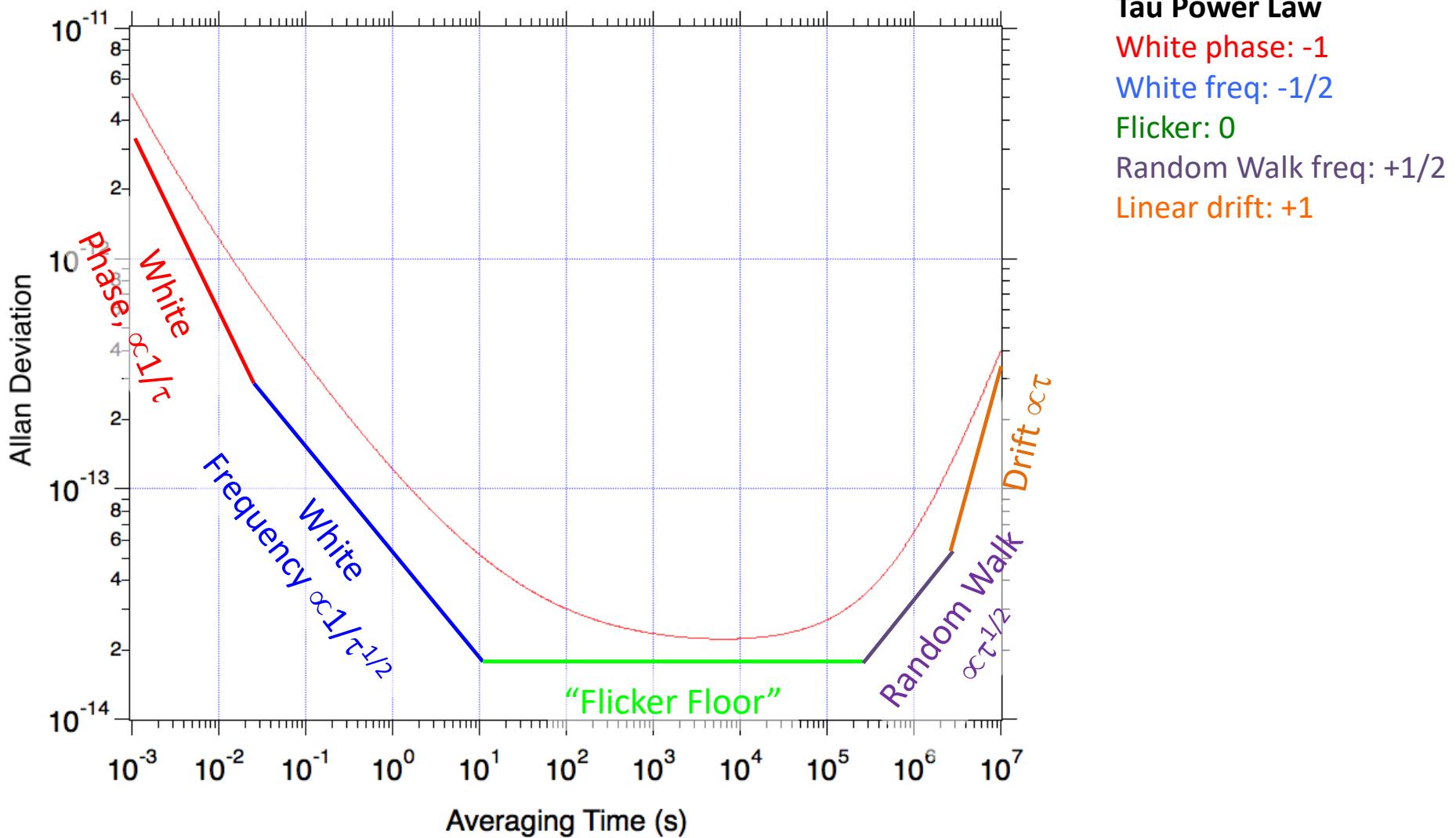
Flicker noise DOES NOT diverge

Compare to Std Deviation:

$$\sigma_{sdev}(\tau) = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \mu)^2}$$

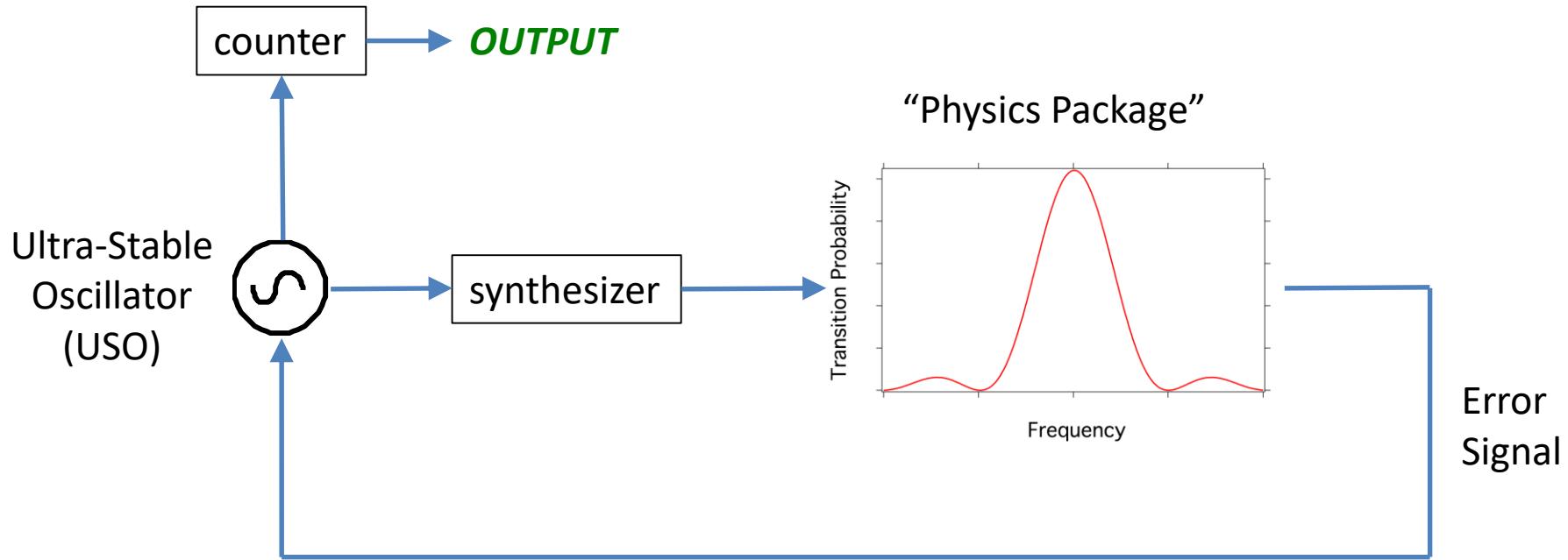
Flicker noise DIVERGES

How to Interpret the Allan Deviation



What is an Atomic Clock?

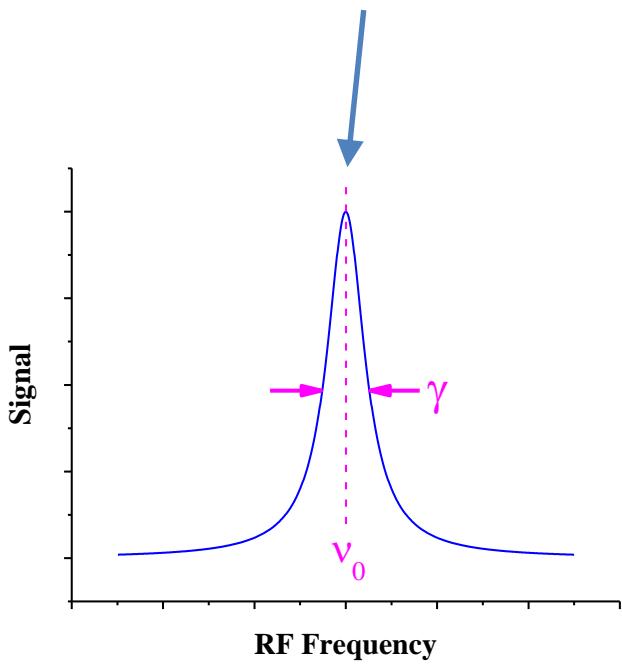
Atomic Clock Schematic



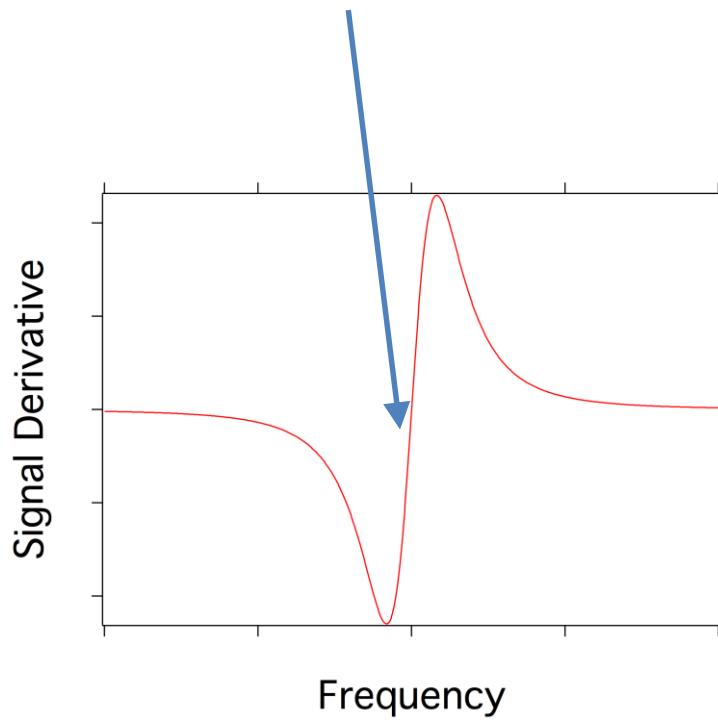
The Physics Package is a very narrow (high-Q) passband filter
For most high performance microwave atomic clocks, $Q > 10^{10}$

Maximize sensitivity “on resonance”

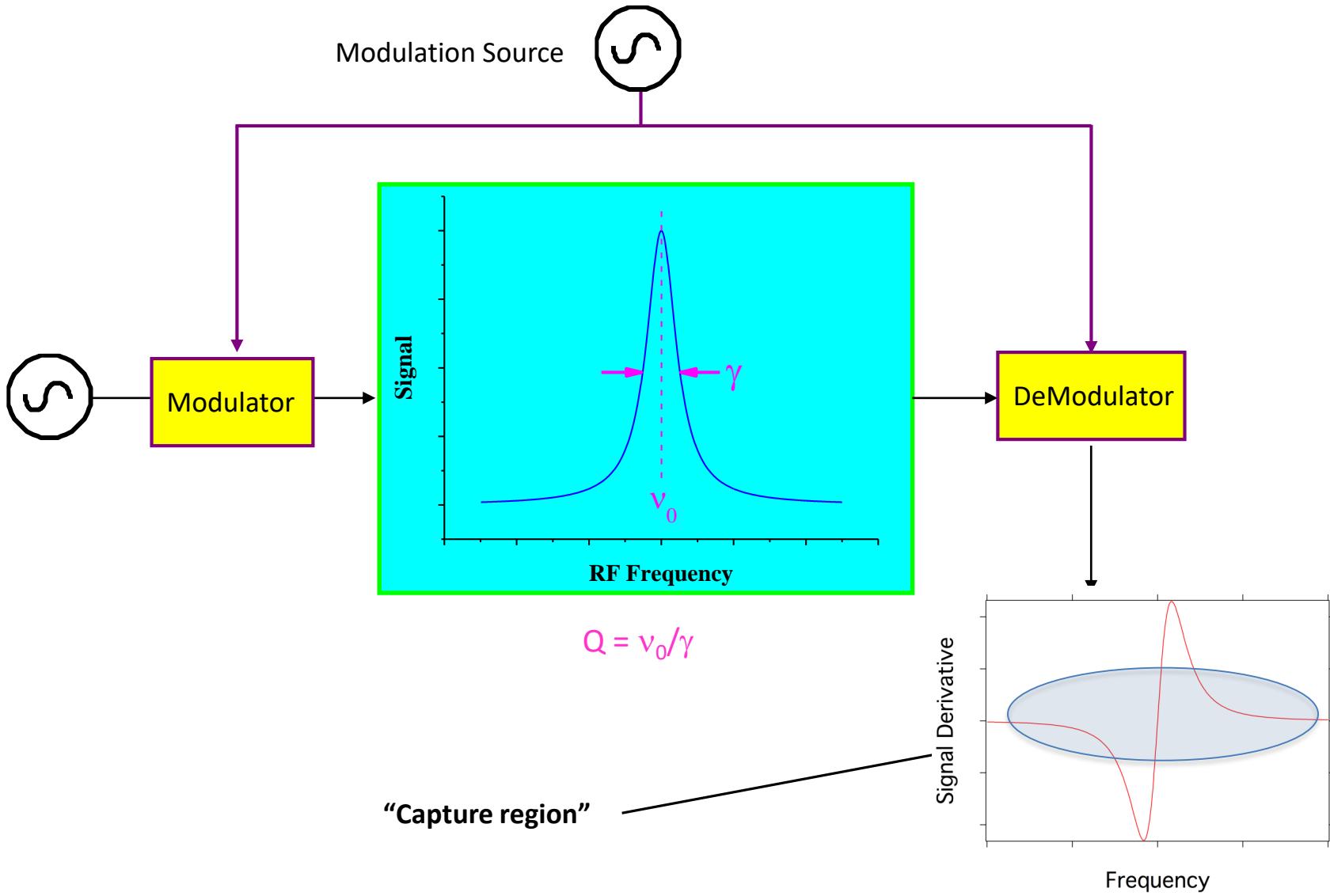
Single measurement is maximally **INSENSITIVE** to Δf on resonance



A difference measurement is maximally **SENSITIVE** to Δf on resonance



Atomic Clock Schematic: Modulation



Basic Microwave Atomic Clock Physics

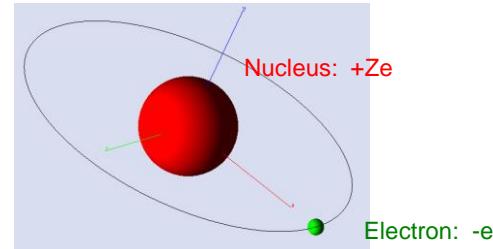
- What is oscillating? Passive vs. Active clocks
- Frequency perturbations
 - Electro-magnetic: Light shift (AC Stark shift)
 - Magnetic: (Zeeman) shift, 1st and 2nd order
 - Motional/Relativistic: Doppler shift, 1st and 2nd order
 - Note: Lamb-Dicke confinement eliminates 1st order Doppler
 - Collisions: Pressure shift

Basic Microwave Atomic Clock Physics: Atomic Interactions

- Hyperfine transitions: 1-40 GHz
- Atomic interactions:

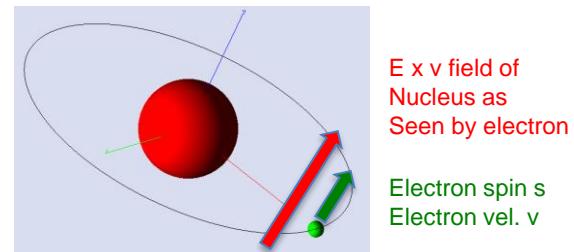
- Coulomb interaction

$$\Delta E = -\frac{1}{4\pi\epsilon_0} \frac{Ze^2}{r}$$

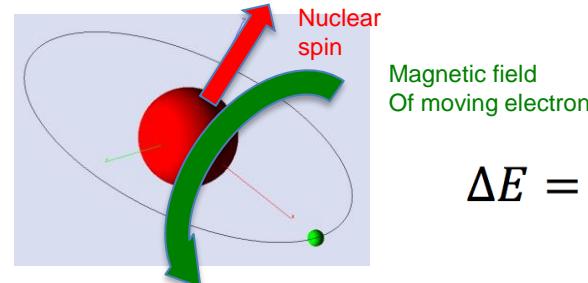


- Fine structure: electron spin interacts with nuclear electric field (optical)

$$\Delta E = -\bar{\mu}_S \cdot \bar{B} = \frac{2\mu_B \bar{s}}{c^2} \cdot (\bar{E} \times \bar{v})$$

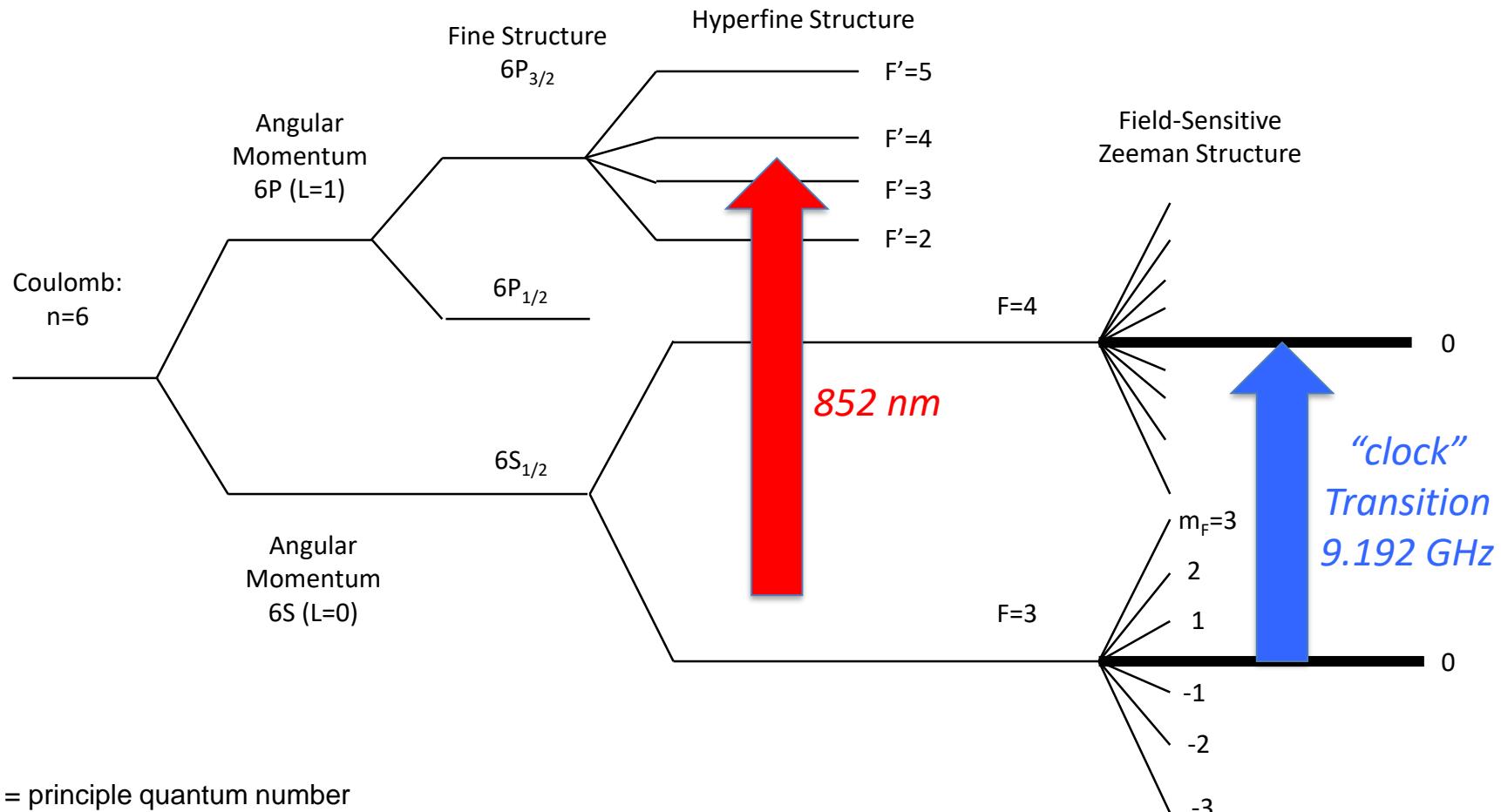


- Hyperfine structure: nuclear spin interacts with the magnetic field created by the moving electron (microwave)



$$\Delta E = -\bar{\mu}_N \cdot \bar{B}_{el}$$

Basic Microwave Atomic Clock Physics: Simplified Cesium Atomic Level Structure



N = principle quantum number

L = angular momentum quantum number

S = electron spin quantum number

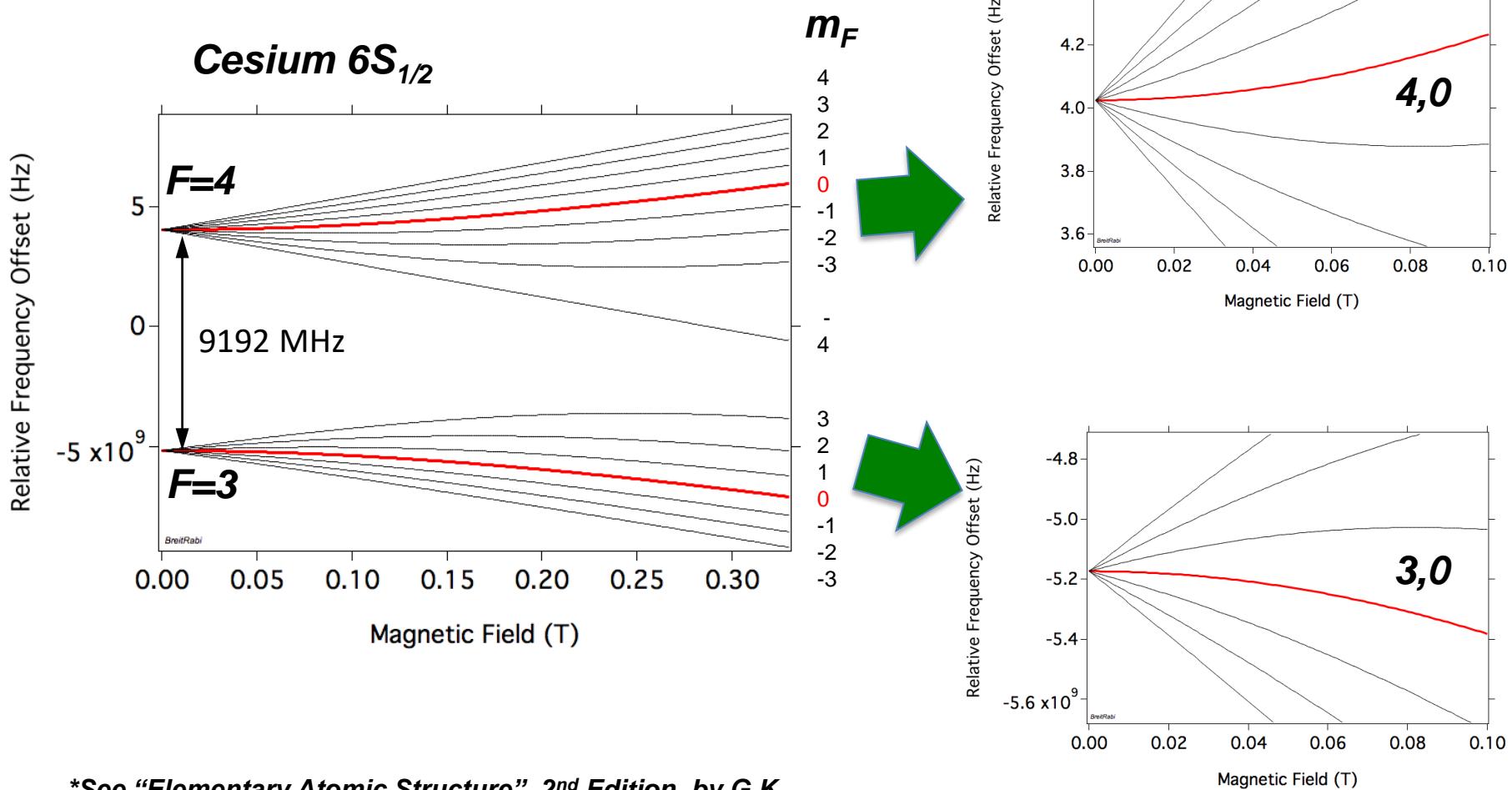
I = nuclear spin quantum number

J = $L+S$: total electron angular momentum

F = $I+J$: total atomic angular momentum

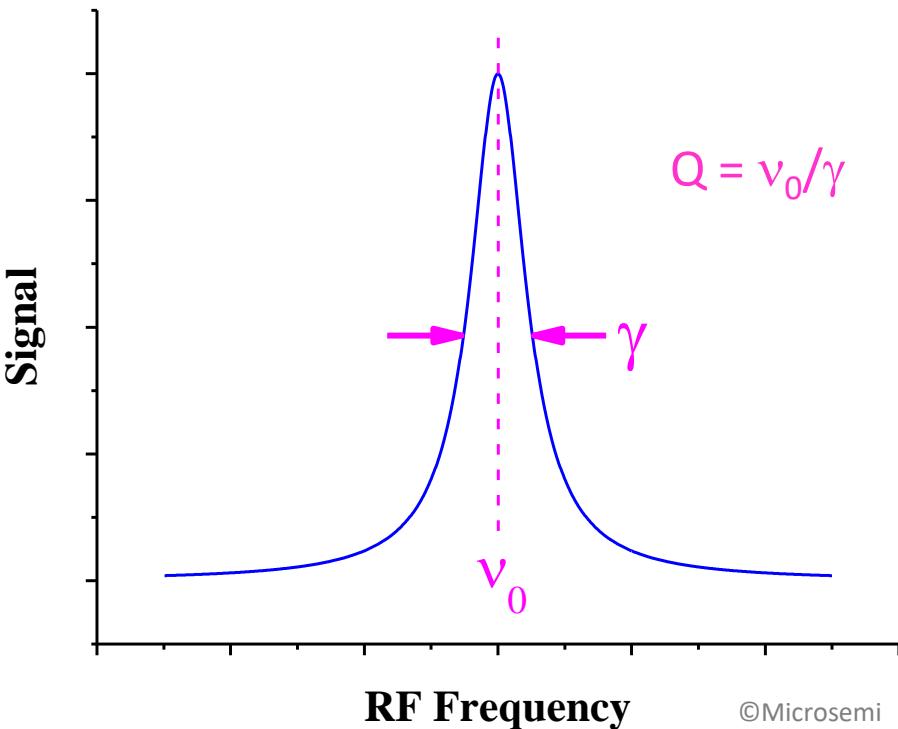
Integral F => existence of first-order field-insensitive $m_F=0 - m_F'=0$ transition

Energy Levels: A closer look at Zeeman structure*



*See "Elementary Atomic Structure", 2nd Edition, by G.K. Woodgate, Oxford University Press, eq. 9.80, p. 193

Basic Microwave Atomic Clock Physics: Atomic Clock Stability



Remember Equation 1:

$$\sigma(\tau = 1 \text{ sec}) = \frac{1}{(S/N)_{1\text{Hz}} \times Q}$$

- ⌚ S/N is limited by atomic beam flux
- ⌚ ν_0 is resonance frequency – choice of atom
- ⌚ γ is linewidth – limited by Fourier transform of measurement time, $gT = \text{constant}$

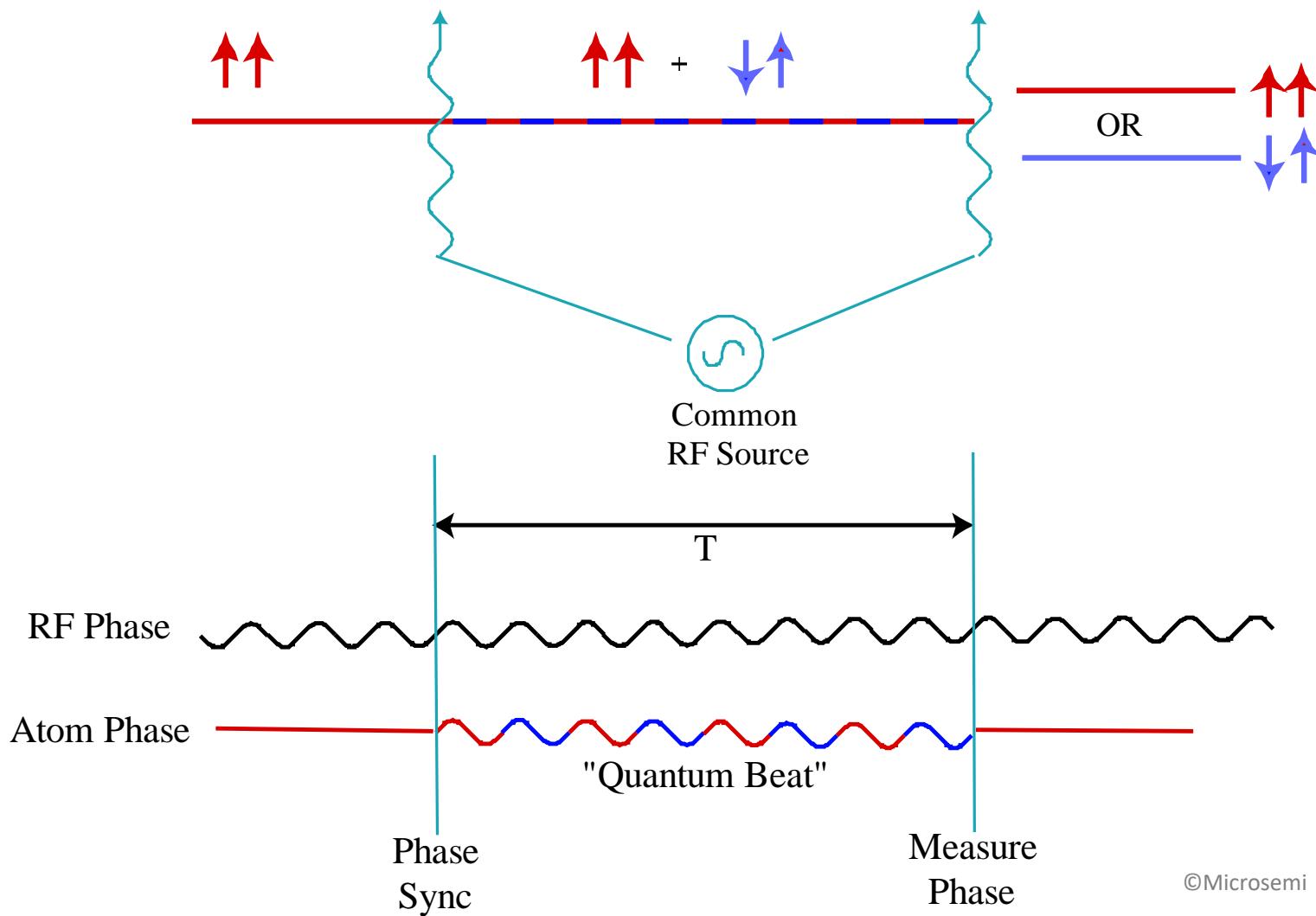
In an atomic beam, interaction time (and thereby γ) is limited by time-of-flight of atoms through microwave field.

It's very difficult to construct a stable uniform microwave field longer than a wavelength.

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Basic Microwave Atomic Clock Physics

Ramsey Separated Oscillatory Fields



A Brief History of Atomic Clocks

- Stern-Gerlach (1922)
- Nuclear Magnetic Resonance (1938): Rabi, Ramsey
- Separated oscillatory fields (1949) – invention
- Separated oscillatory fields – in laboratory clocks
- First operational clocks (1955) – Essen and Perry
- Masers – Ramsey
- Lasers (1960)
- Celestial time -> atomic time (1967)
- Commercial cesium beam clocks (1964 ->)
- Laser Cooling (1978)
- Ion trapping (1950's)
- Optical clocks part 1 (1980's – 1990's)
- Atomic fountain clocks (1995)
- Ultra stable clocks part 1 (1980's ->)
- Combs (1999)
- Optical clocks part 2 (1999)
- Ultra stable microwave clocks part 2 (2005)
- Clocks in space

Commercial vs. Laboratory

Goals

- “Robustness”
- Continuous operability
- Fieldability
- Stability
- accuracy



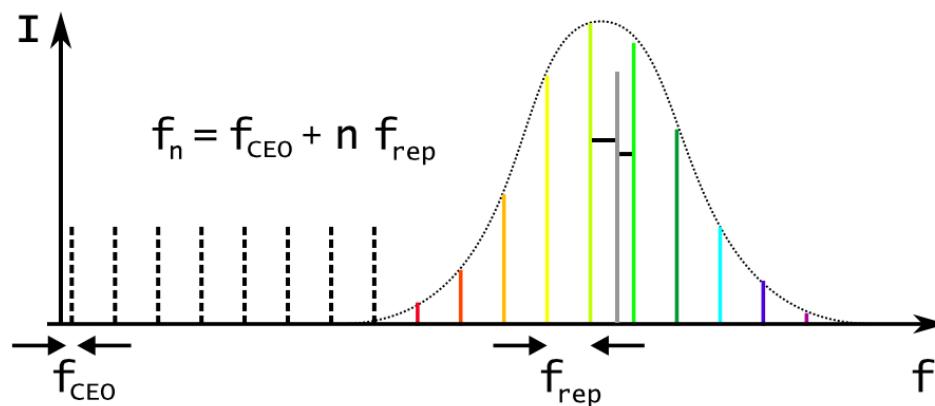
Laboratory/Timekeeping



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Microwave vs. Optical

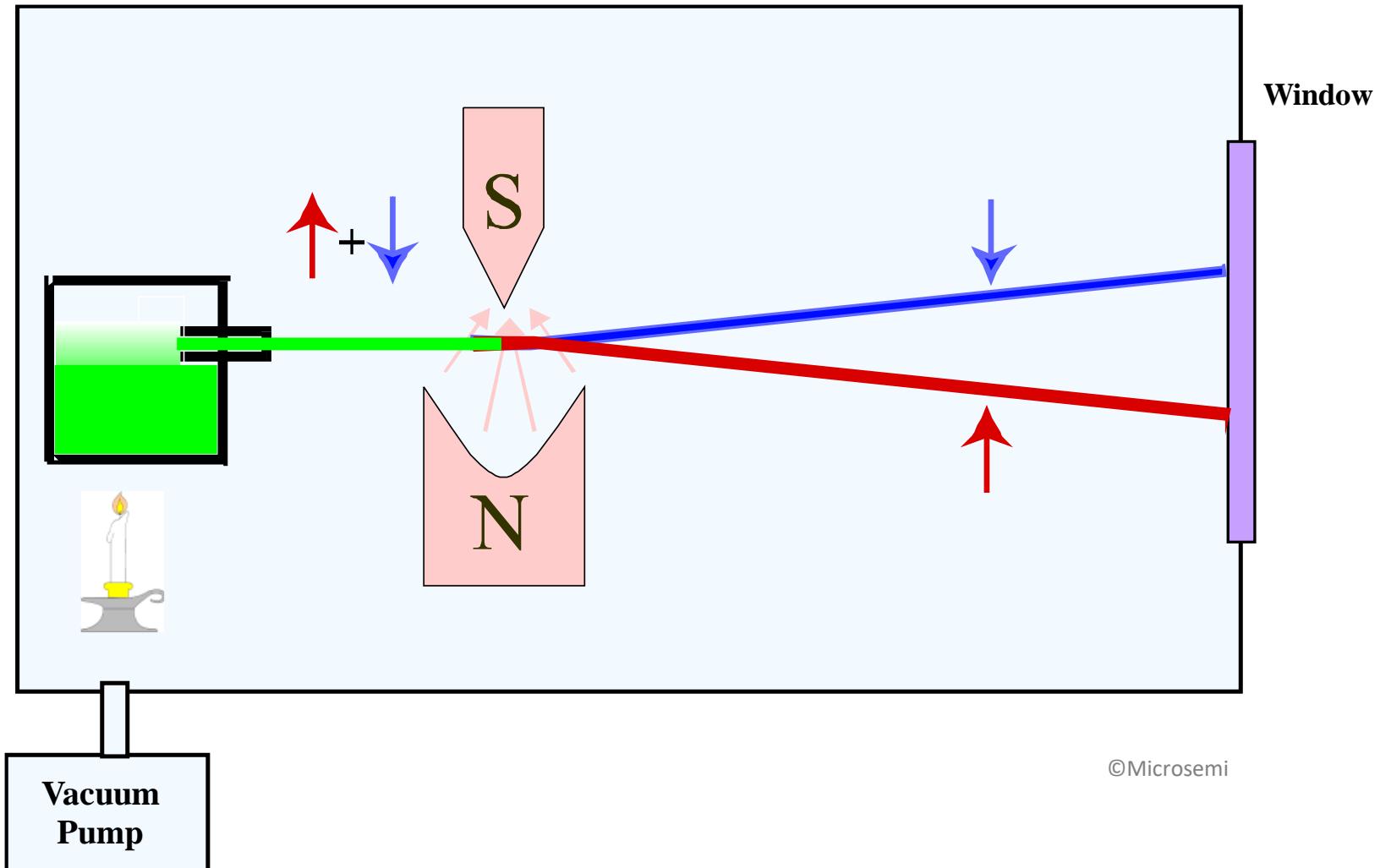
- GHz vs. 10^{14} - 10^{15} Hz: Q
- Robustness
- Systematic sensitivity
- Lasers
- Combs (See Optical Clocks tutorial)



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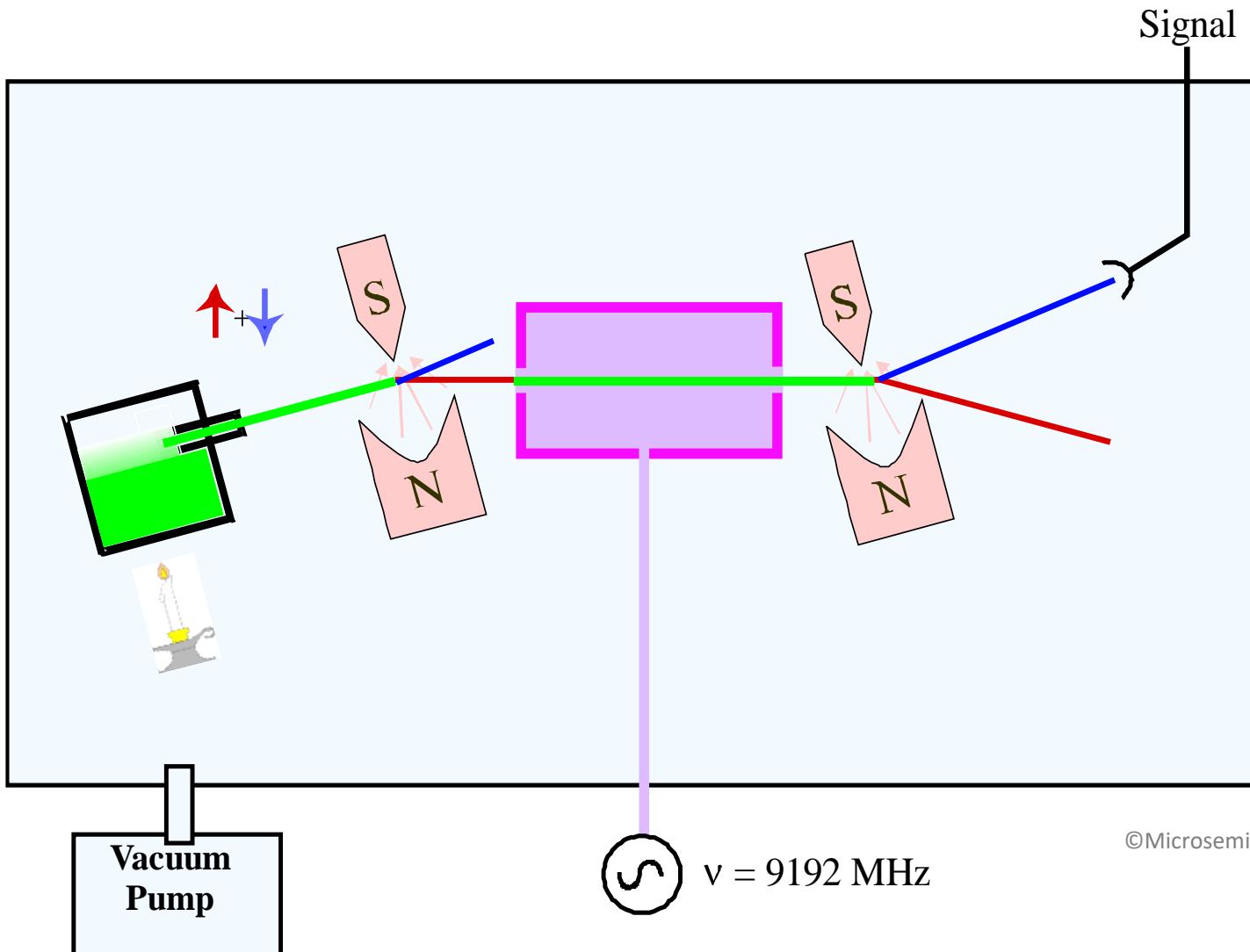
Microwave Atomic Clock Examples: The Cesium Beam Tube Clock

Cesium Beam: The Stern Gerlach Effect



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Cesium Beam Tube: Magnetic Resonance

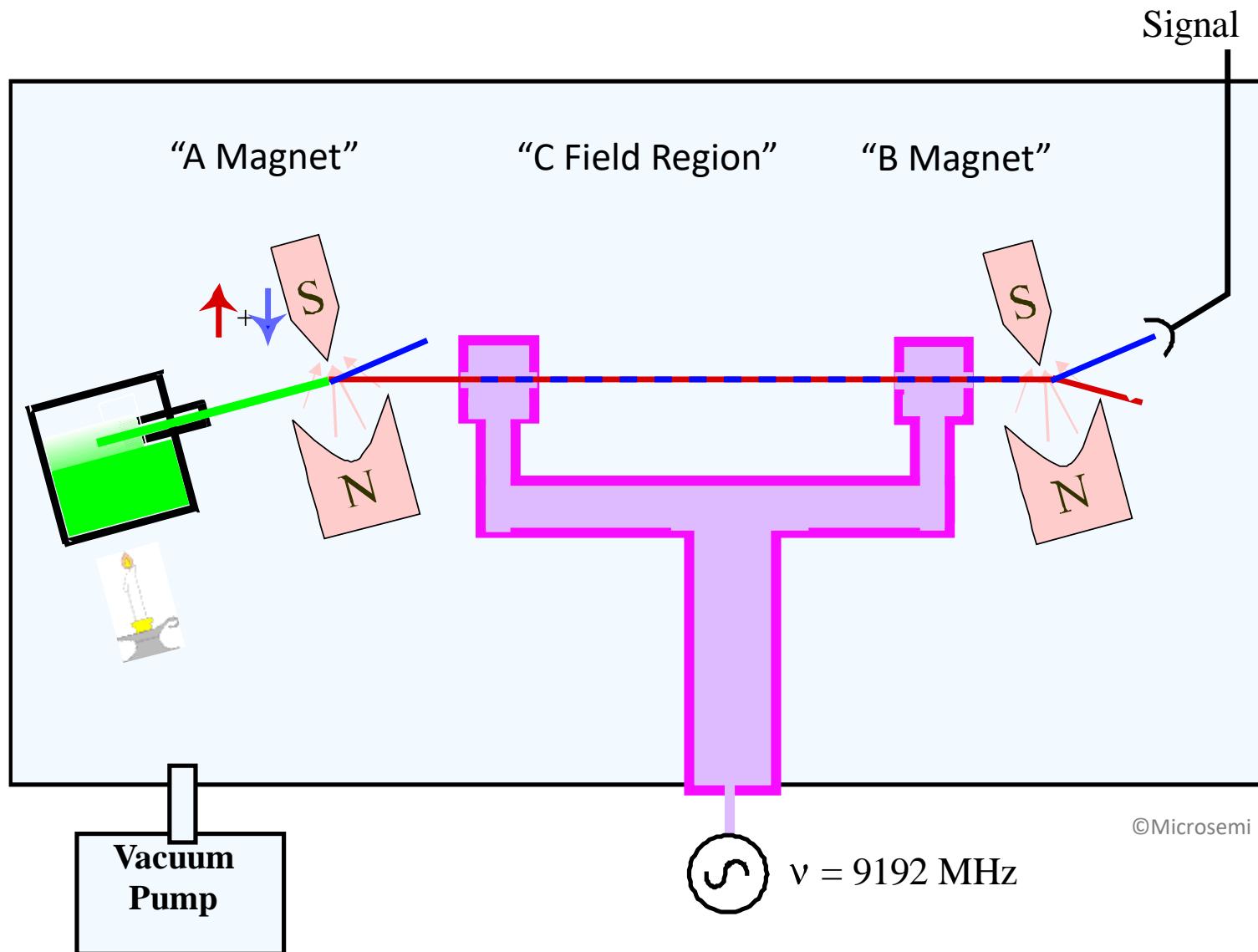


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Cesium Level diagram (slide 18)

25

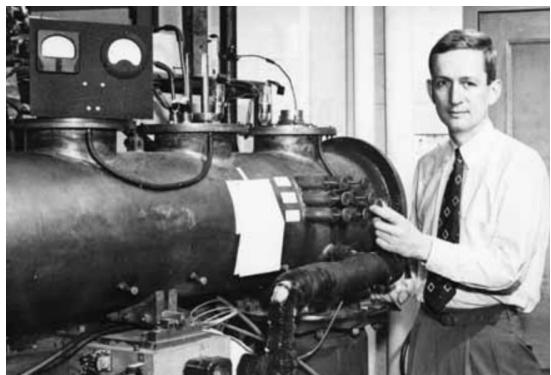
Ramsey: Separated Oscillatory Fields



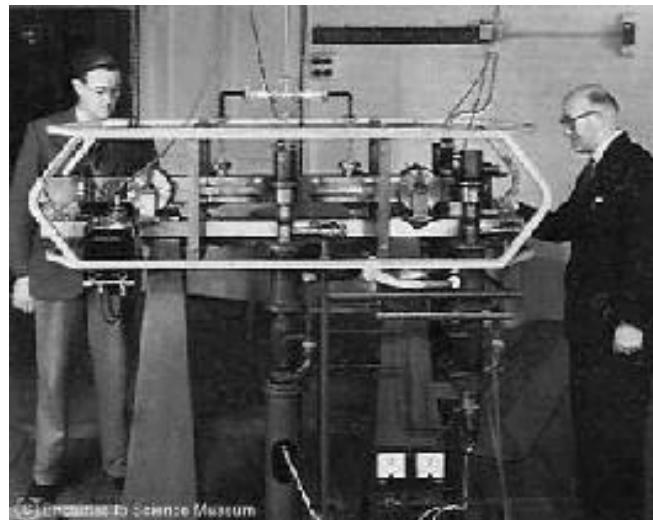
Cesium Beam Tube

1955 NPL Cesium Clock

Normal Ramsey



Essen & Perry 1953



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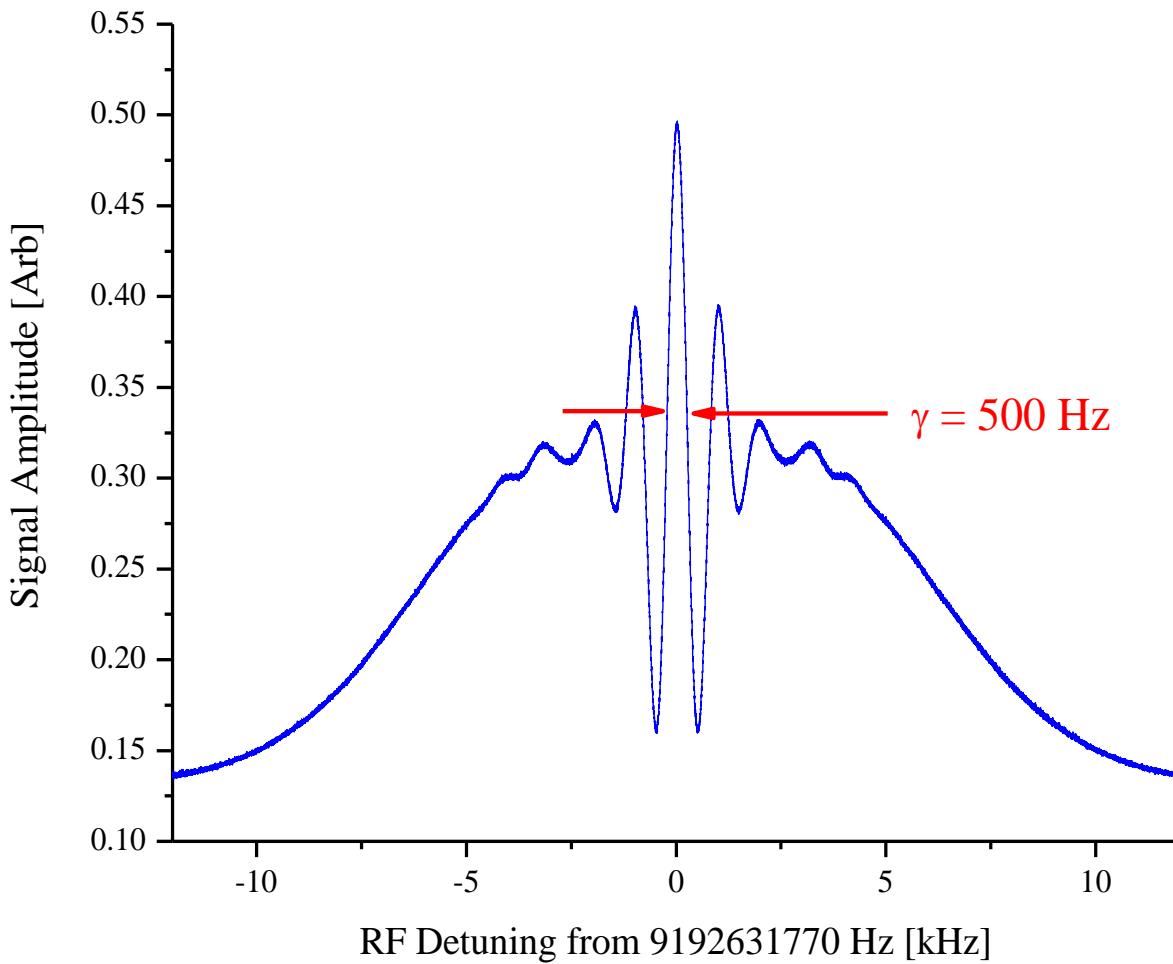
NBS-6 circa 1975

Courtesy of Microsemi



PTB CS1 (1965 - present)

Cesium Beam Tube Spectrum



$$Q = 2 \times 10^7$$
$$(S/N)_{1\text{Hz}} = 3000$$

$$\sigma(1\text{sec}) = \frac{1}{(S/N)_{1\text{Hz}} \times Q}$$
$$\approx 2 \times 10^{-11}$$

Linewidth (and Q) limited by time-of-flight of atoms through microwave region
Signal/Noise limited by atomic beam flux: $Noise \propto \sqrt{Signal}$

Cesium Beam Tube Instruments



Laboratory/Timekeeping

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Telecom

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Space/GPS

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Cesium Beam Frequency Standard Summary

+ “Primary” frequency standard

- Absolute accuracy (within known limits)
- No long-term drift of frequency
- “No” environmental sensitivity
- No retrace (power cycle) error

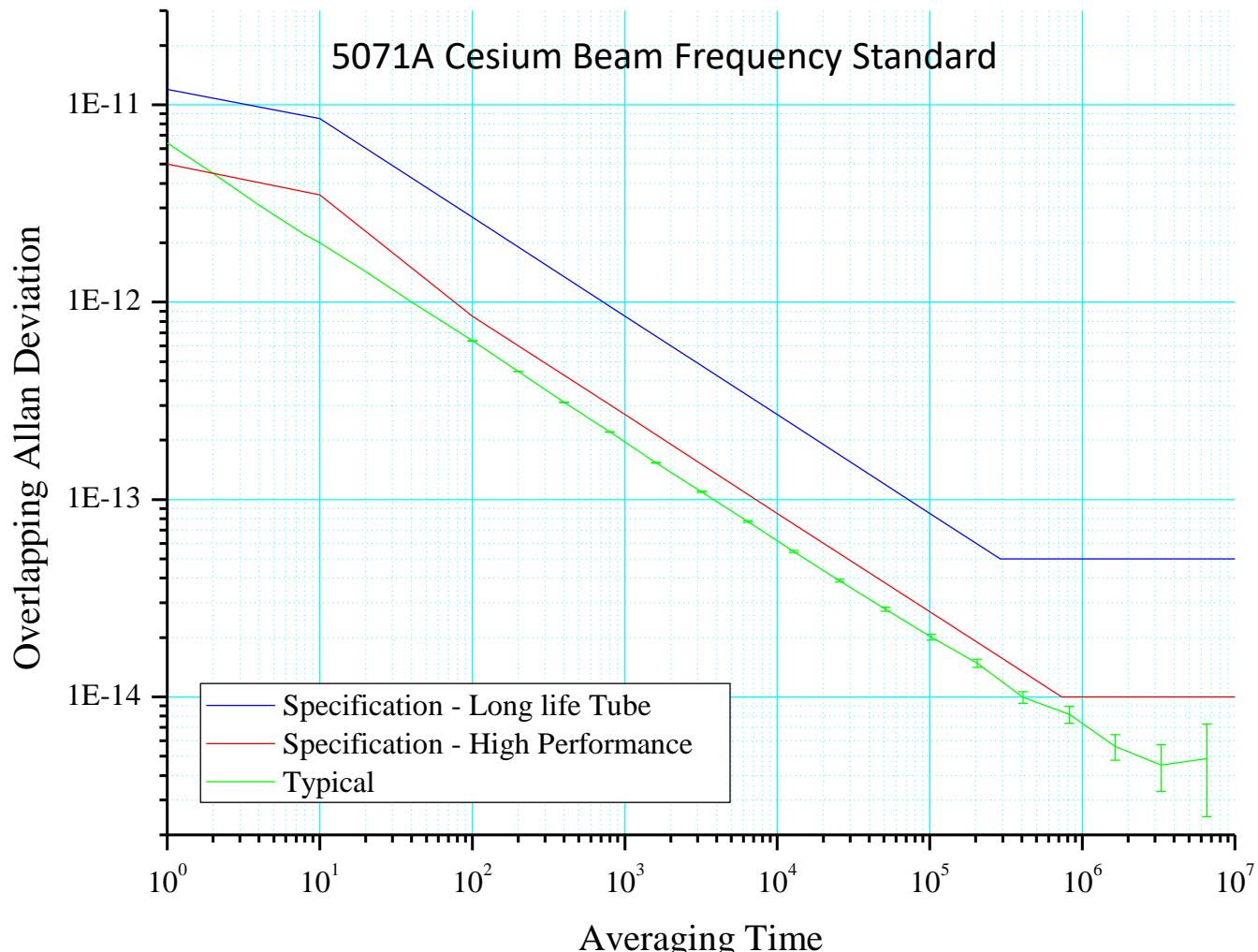
+ Mature Technology

- > 10,000 CFS built over 40-year history
- High reliability

- Relatively large, complex and expensive

- 3U Rack-mount, ≈50 Watts, \$50-75K
- Commercial instrument of choice for absolute accuracy and reliability
 - Laboratory frequency reference for science and calibration
 - Major contributor to international time-keeping (UTC)
 - Top-level telecom synchronization

Commercial Cesium Beam Tube Performance Summary



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Short term stability: $4\text{e-}12/\sqrt{\tau} - 2\text{e-}11/\sqrt{\tau}$
Accuracy: < 1e-13 (HP/Agilent/Microsemi)

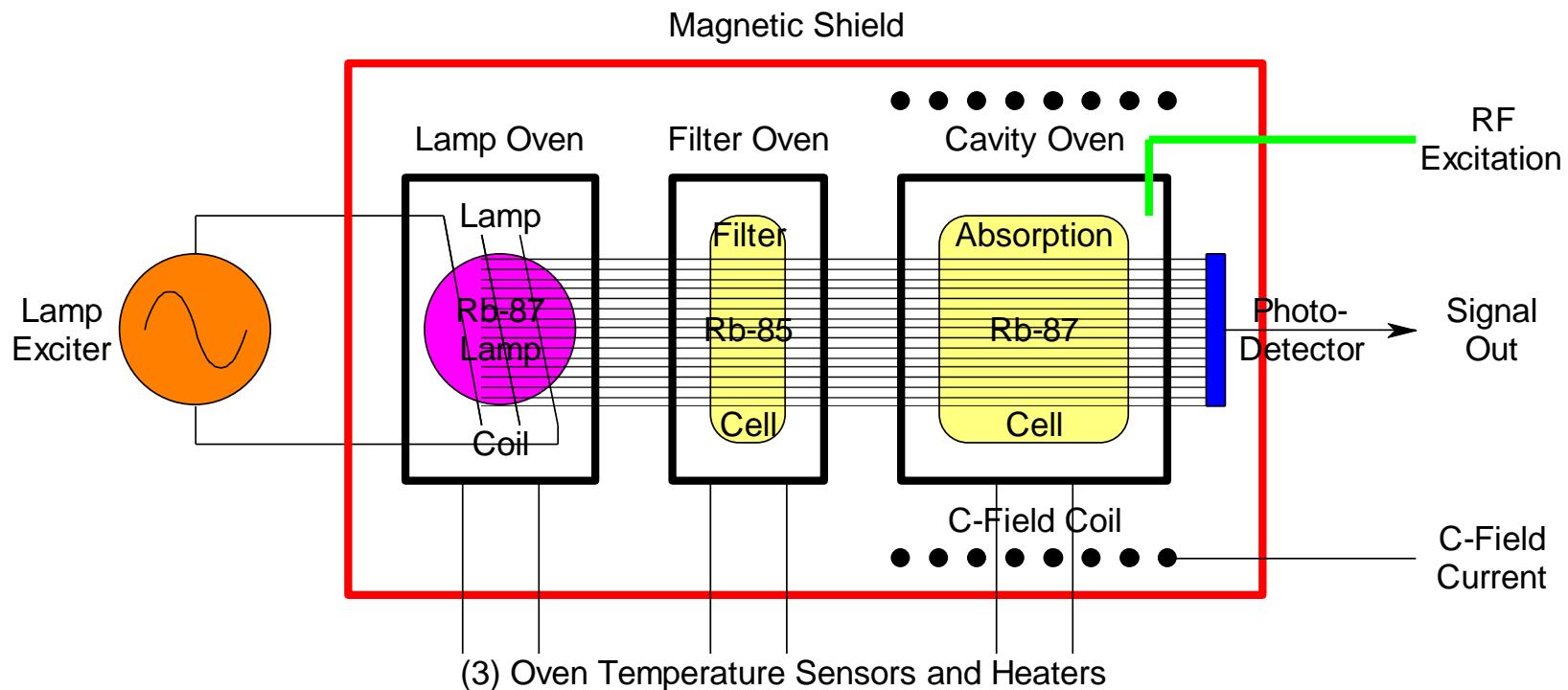
Microwave Atomic Clock Examples: The Rubidium Gas Cell Clock

Rubidium

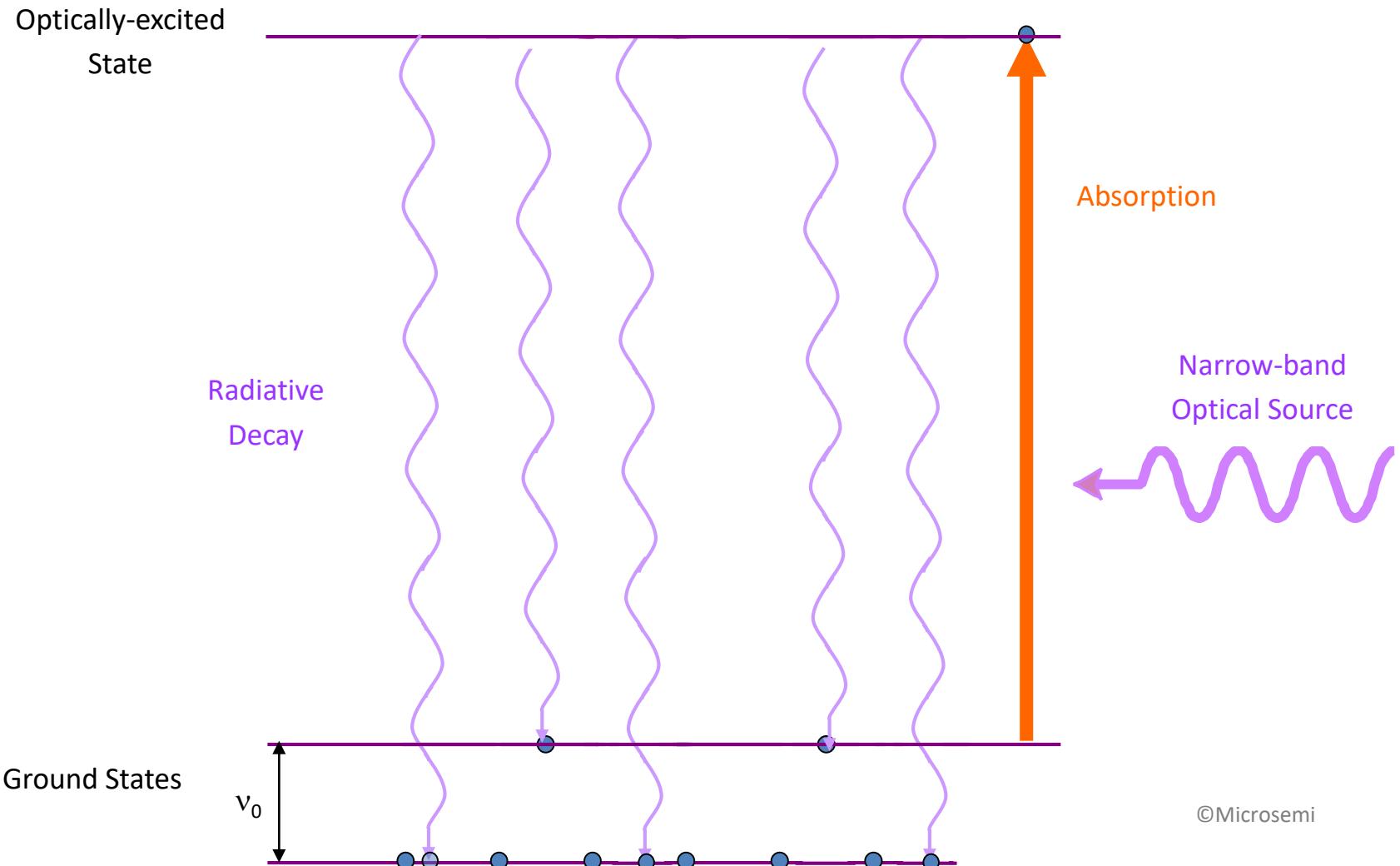


Courtesy Microsemi

Rb Gas Cell Physics Package

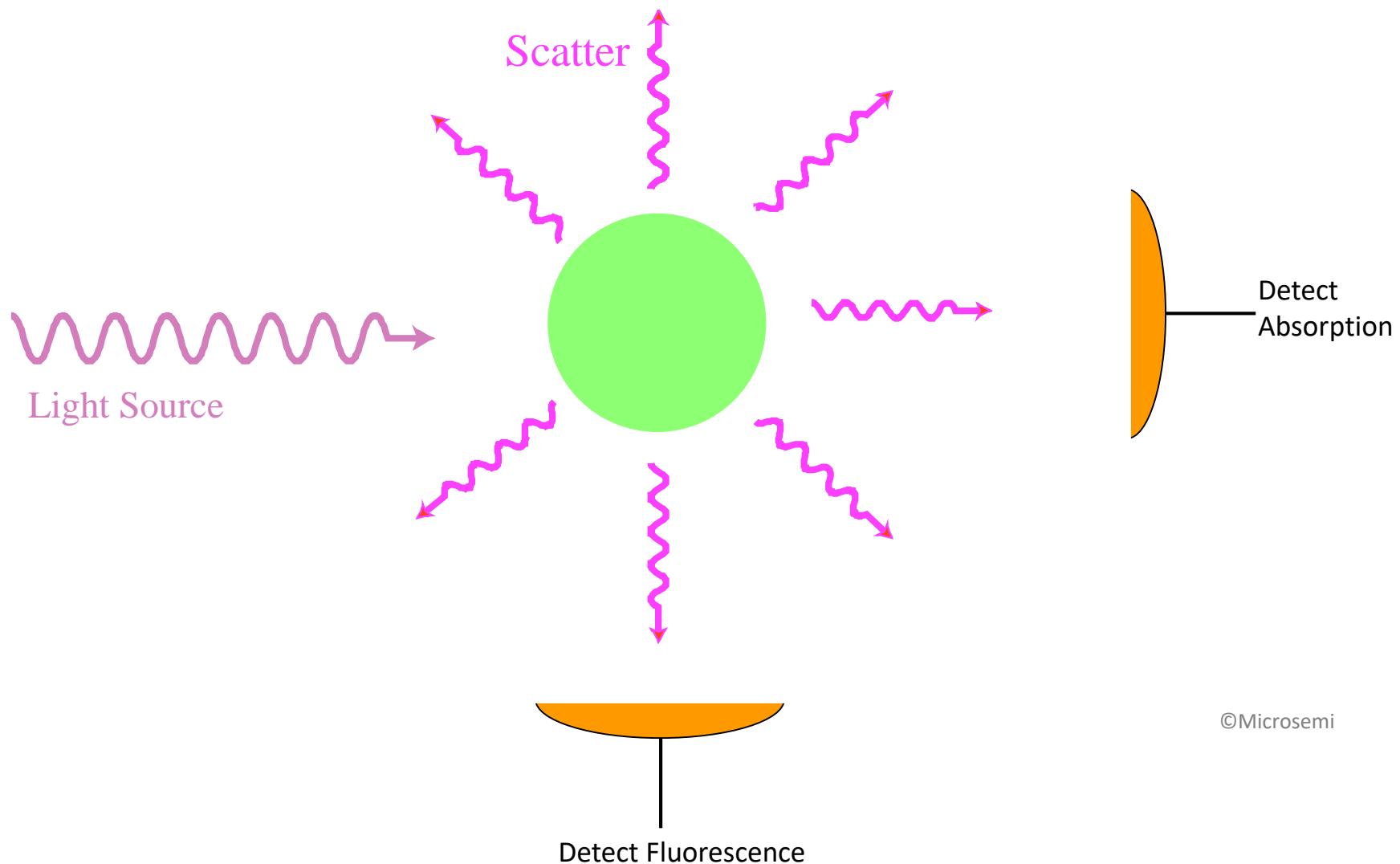


State selection by optical pumping



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State detection by optical scattering

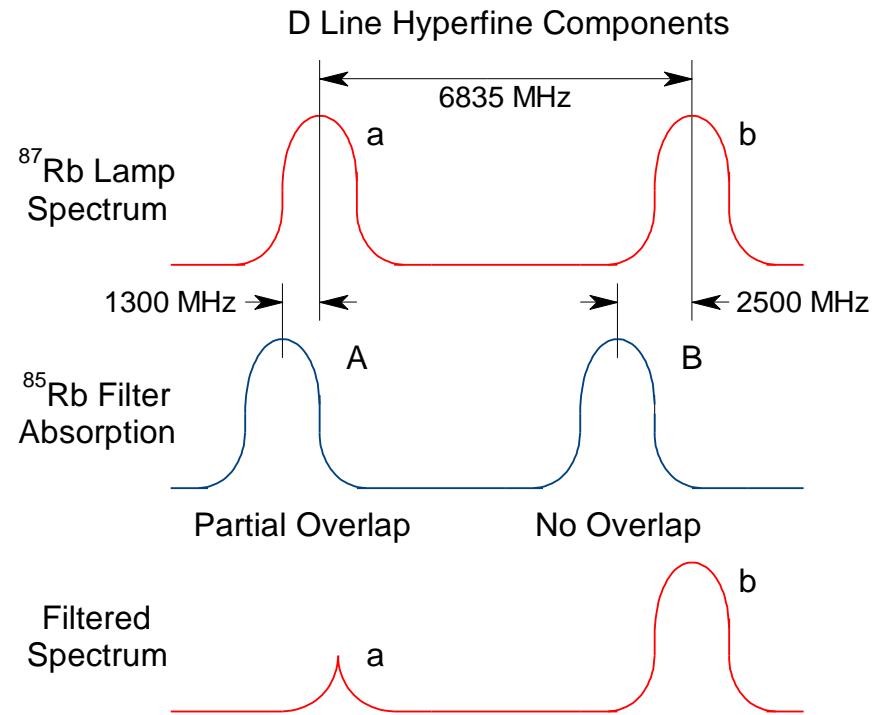


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Hyperfine filtration in rubidium

Carver & Alley 1958

“Fortuitous” overlap between the optical absorption lines of the two naturally-occurring isotopes, ^{85}Rb and ^{87}Rb .

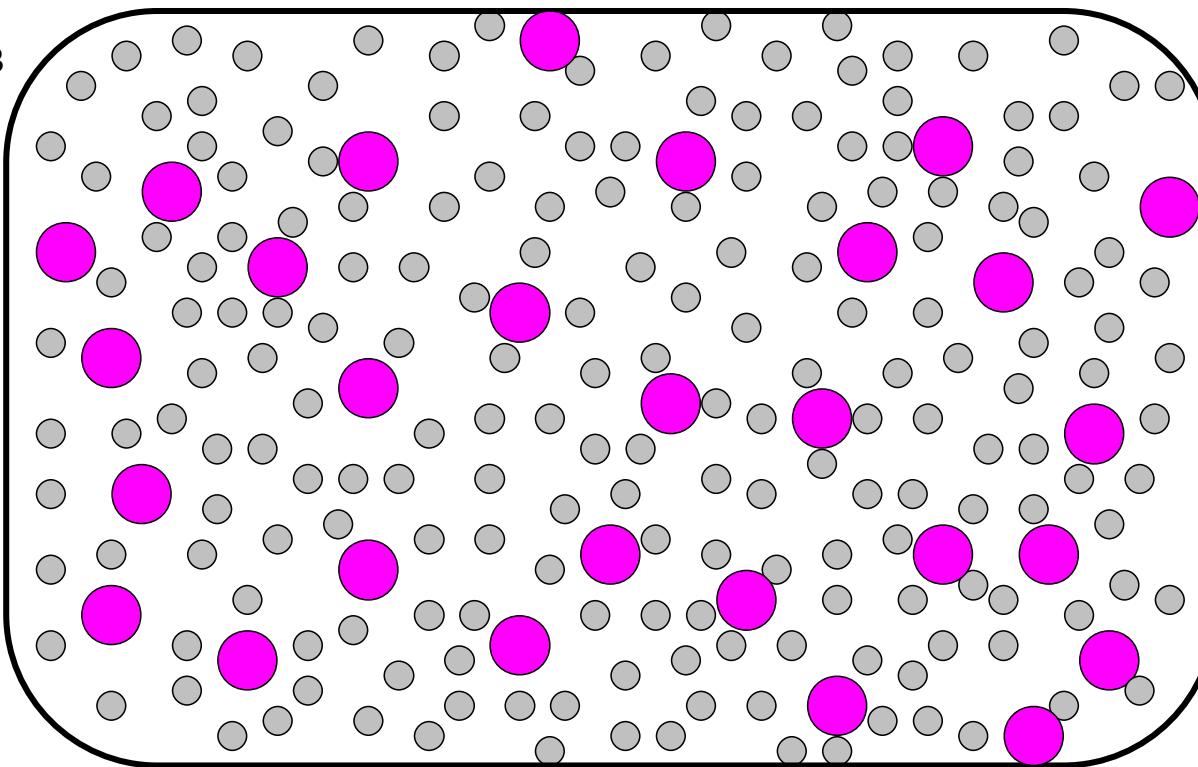


Isotopic Filtering of Rubidium 87 D Lines

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Rubidium gas cell confinement

Dicke 1953

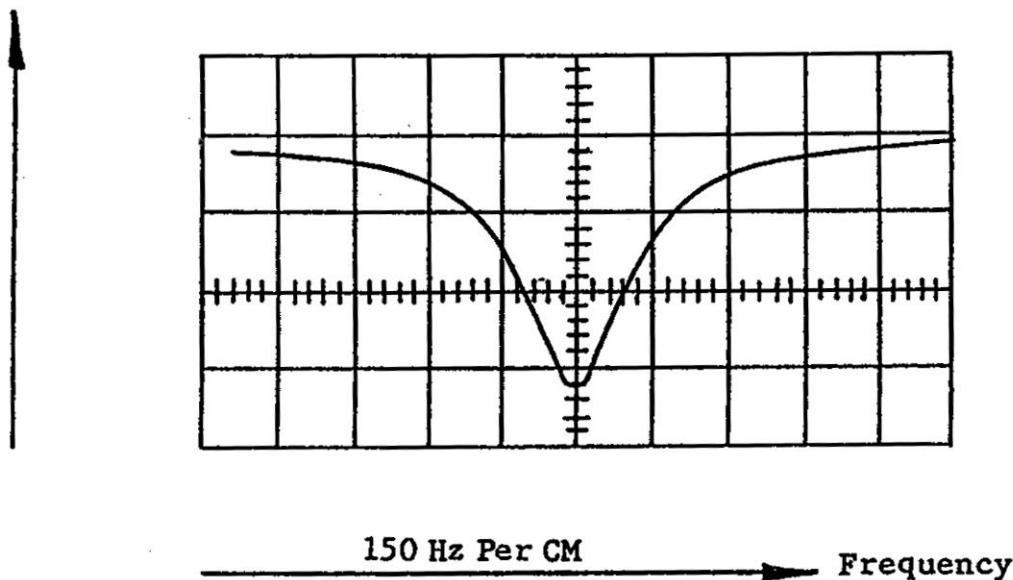


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- ⌚ RbO atomic resonance linewidth, γ , is limited by decoherence of population inversion due to collisions with walls and other Rb atoms
- ⌚ Nitrogen “buffer gas” atoms “immobilize” Rb with minimal decoherence
 - ⌚ Reduces Rb-Rb and Rb-wall collisions
 - ⌚ Confinement => average velocity=0: Eliminates first-order Doppler shift

Rubidium RF Spectrum

Light Intensity



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$$Q = 2 \times 10^7$$

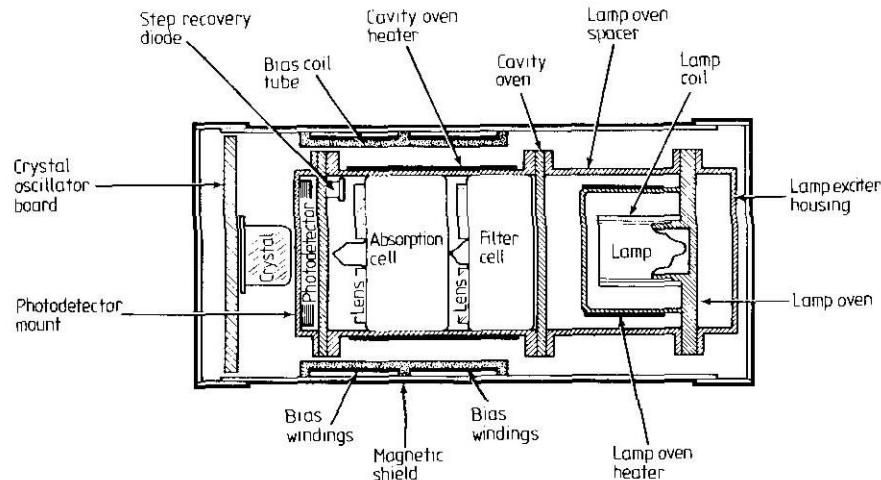
$$(S/N)_{1\text{Hz}} = 3000$$

$$\sigma(1\text{sec}) = \frac{1}{(S/N)_{1\text{Hz}} \times Q}$$
$$\approx 2 \times 10^{-11}$$

Linewidth (and Q) limited by decoherence due to collisions between Rb and Rb, buffer gas, and cell walls
Signal/Noise limited by shot noise of background light: $Noise \propto \sqrt{Intensity}$

Factors that impact rubidium clock performance

- Short-term stability
 - Optimize linewidth & S/N
 - Lamp output – gas mix, RF drive, temperature, etc.
 - Filter cell – gas mix, temperature
 - Resonance cell – Microwave phase stability, gas mix, cell temperature
- Medium-term stability
 - Thermal control circuits, thermal isolation
 - Gas mixtures to reduce temperature sensitivity
 - Ambient pressure effects (“oil-canning”)
 - Magnetic shielding
- Long-term stability (drift)
 - Stability of buffer gas mixture
 - Rubidium migration



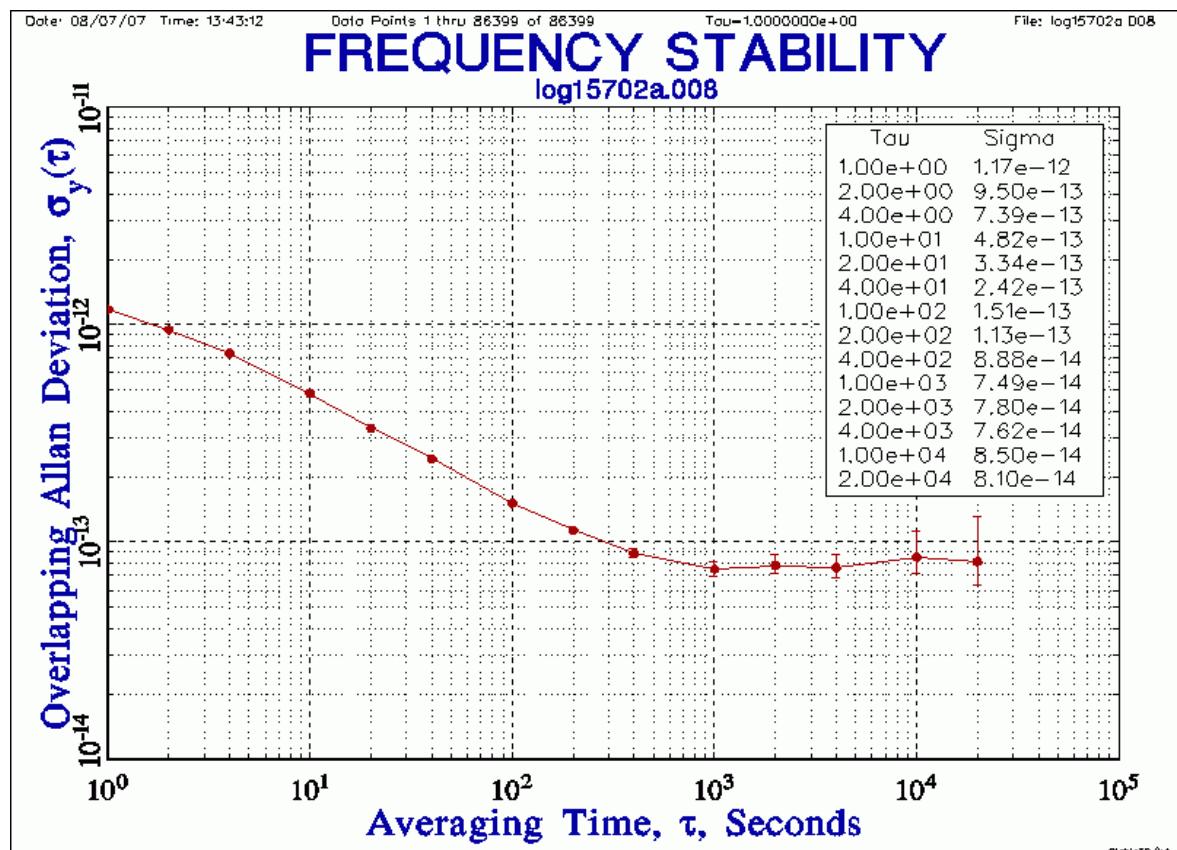
©Adam Hilger
J. Vanier and C. Audoin
“The Quantum Physics of Atomic Frequency Standards,” 1989

EG&G RFS-10 Physics

Rubidum Performance Summary: HP 5065A circa 1970



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www.leapsecond.com

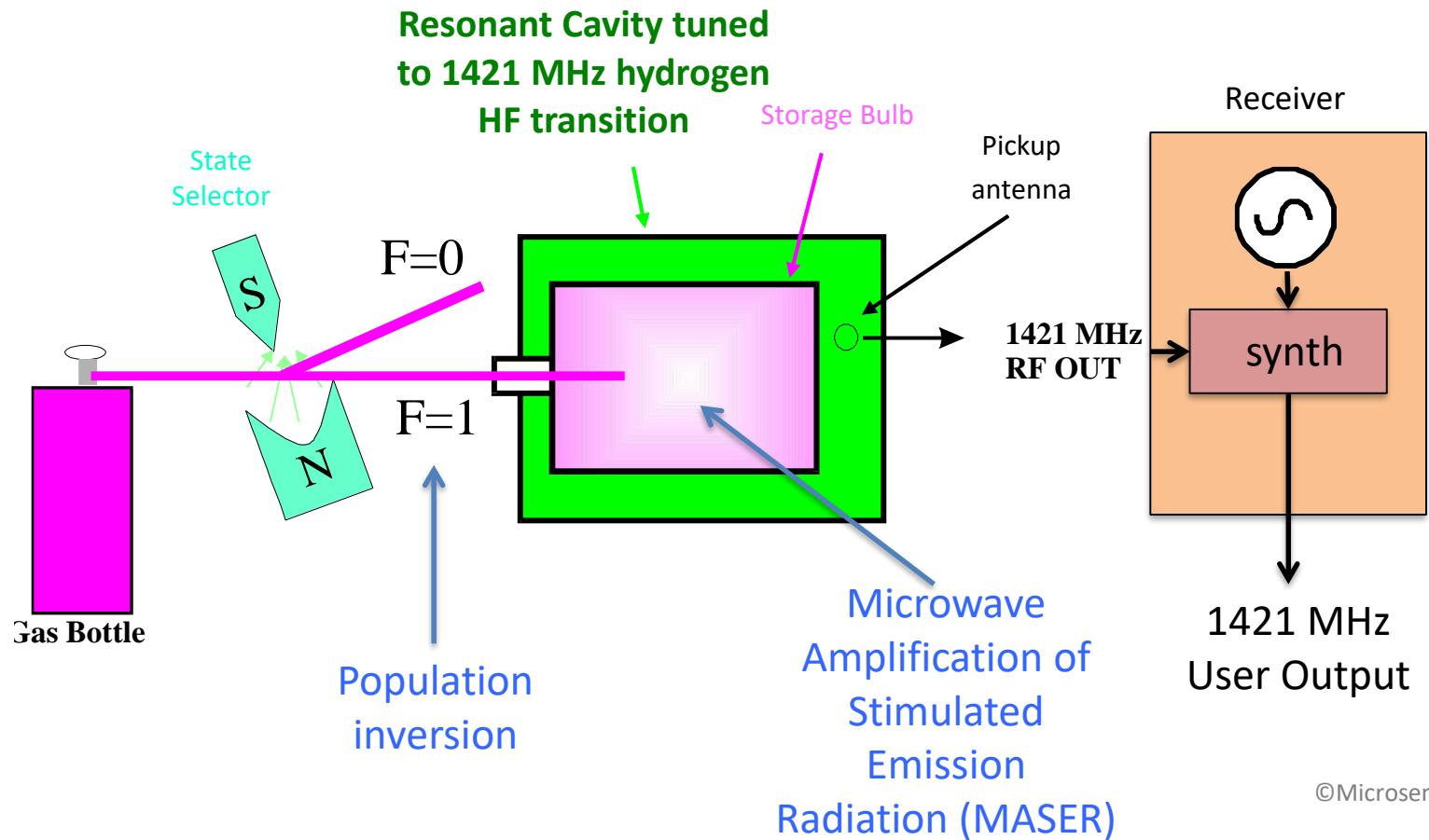


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- **33 Watts, 37 lbs**
- $\sigma_y(\tau) < 5 \times 10^{-12} \tau^{-1/2}$
- **Drift < $2 \times 10^{-11}/\text{month}$**

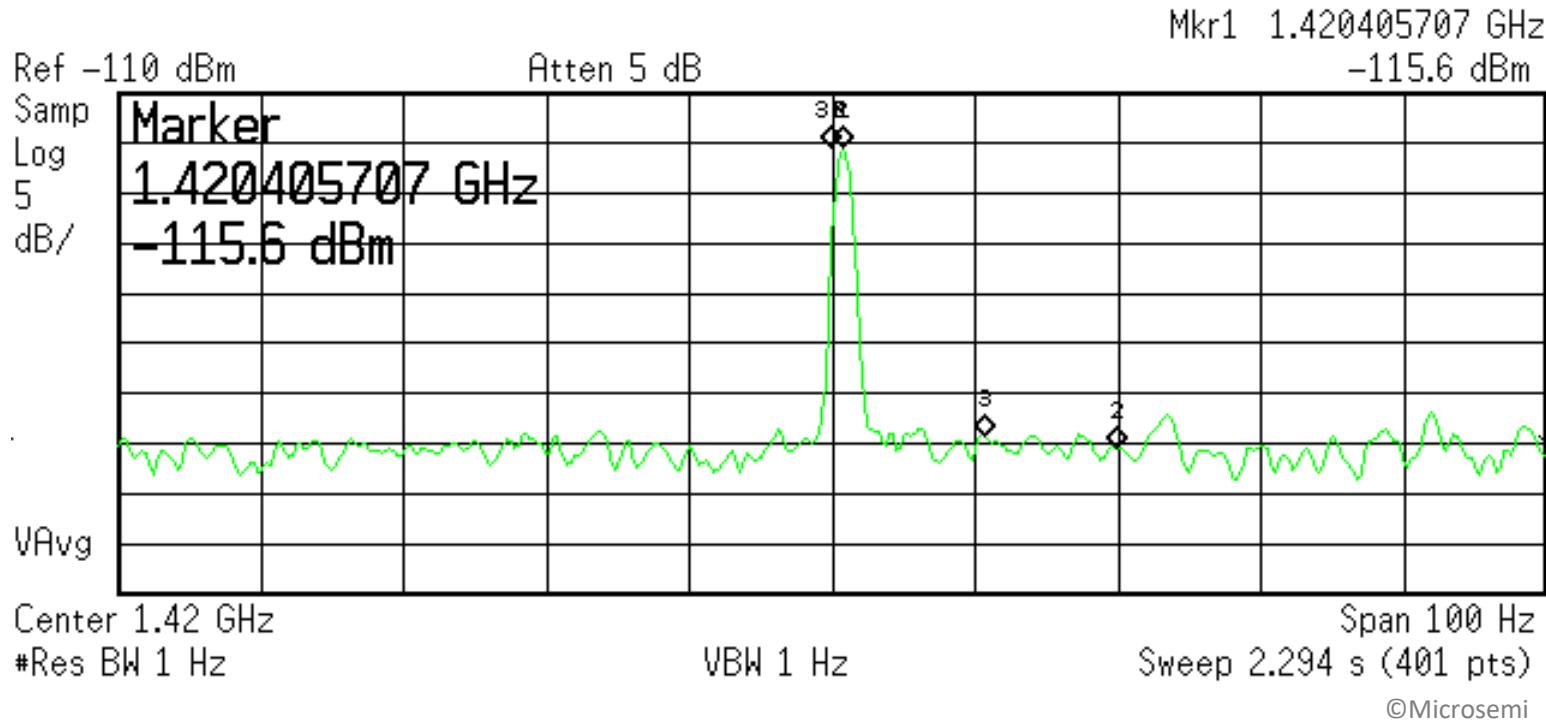
Microwave Atomic Clock Examples: The Hydrogen Maser

Active Hydrogen Maser



- ⌚ Active Device analogous to laser
- ⌚ Excellent short term stability (10^{-13} at 1 s, 10^{-15} at 1000 s)
- ⌚ drifts with cavity/wall properties: $10^{-16} - 10^{-15}$ /day typical

Hydrogen Maser RF Spectrum



- High Q : $\approx (1.4 \text{ GHz}/1 \text{ Hz}) = 10^9$
- Signal is very small: $\approx -110 \text{ dBm}$
- S/N is dominated by front-end electronic noise

Commercial Hydrogen Maser



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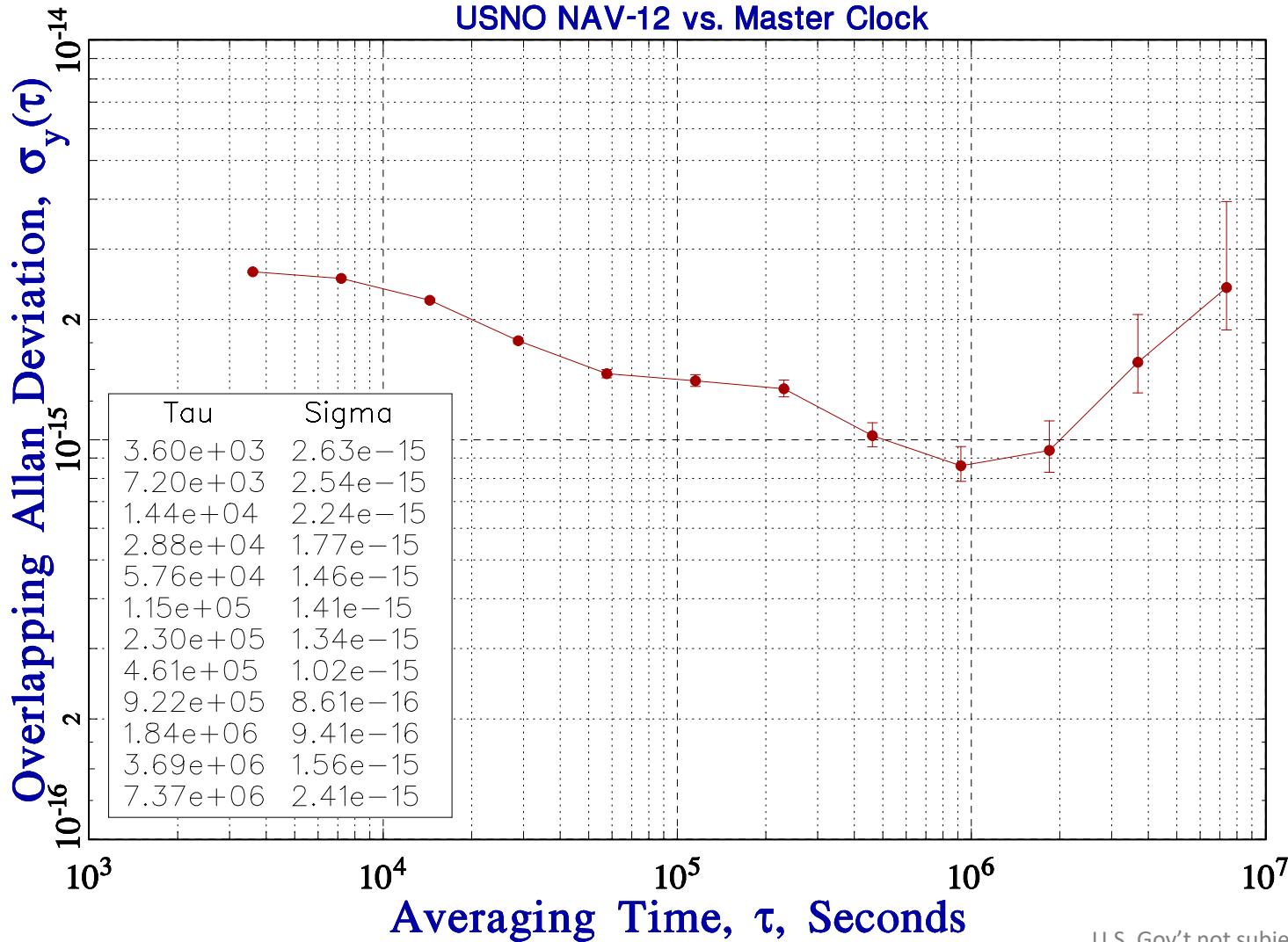
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Microsemi Model MHM2010

Hydrogen Maser Long-term Stability

FREQUENCY STABILITY

USNO NAV-12 vs. Master Clock



U.S. Gov't not subject to copyright
Datum-TI&M

Active Hydrogen Maser Summary

+ Active oscillator

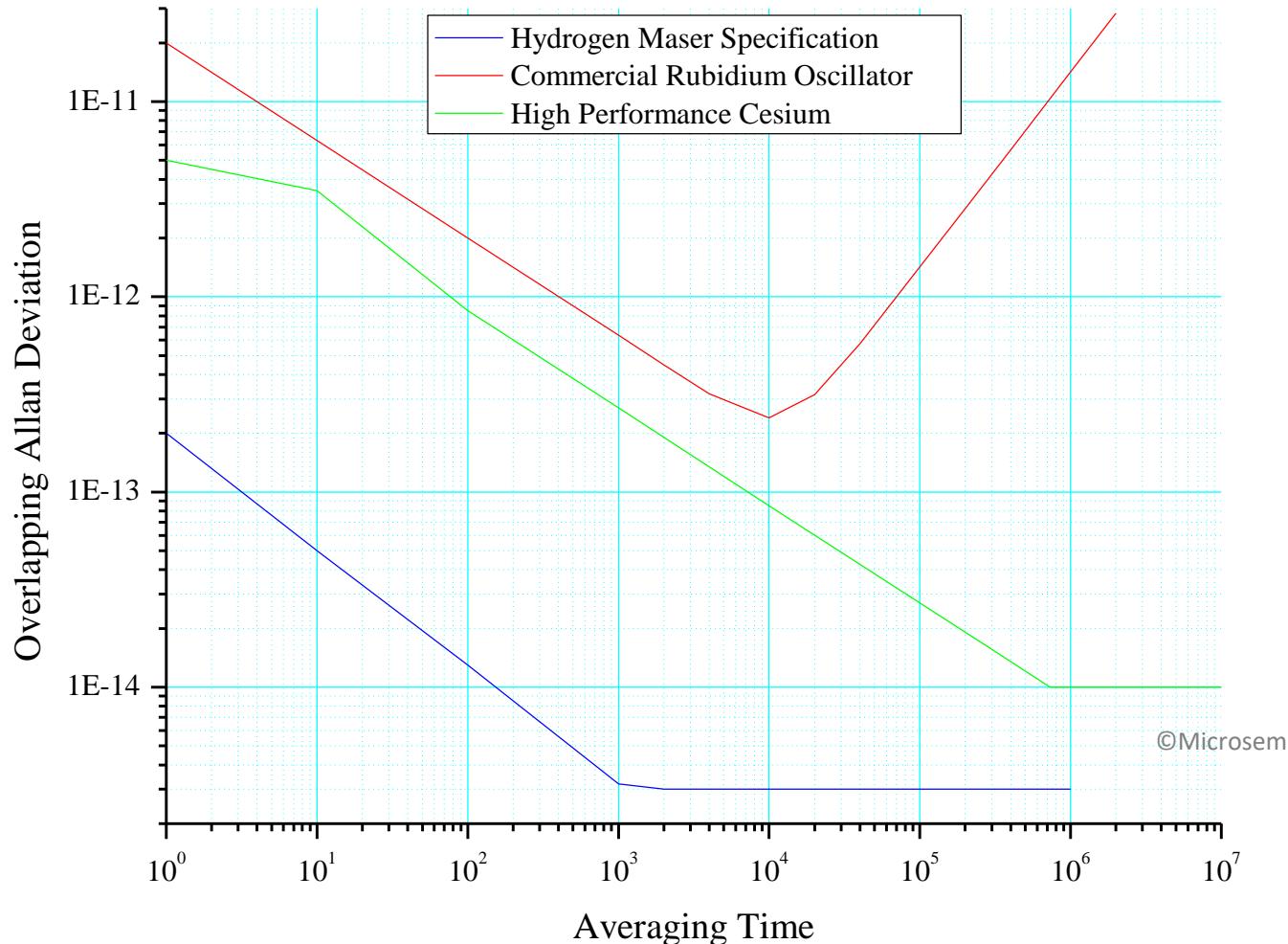
- Gain provided by continuous injection of population-inverted atoms
- Very high Q

+ Good short-term stability

- Limited by noise in electronic receiver for small signal

- Intrinsic accuracy limited by wall properties, cavity detuning, H density
 - Requires periodic frequency calibration
 - Long-term drift
- Relatively large and expensive device relative to other commercial clocks
 - Floor-standing, 150W, about \$200K
 - Typically housed in environmental chamber to minimize perturbations
- Instrument of choice for Ultimate short-term stability
 - Radio astronomy
 - International timekeeping
 - Fundamental science

Active Hydrogen Maser Performance Summary



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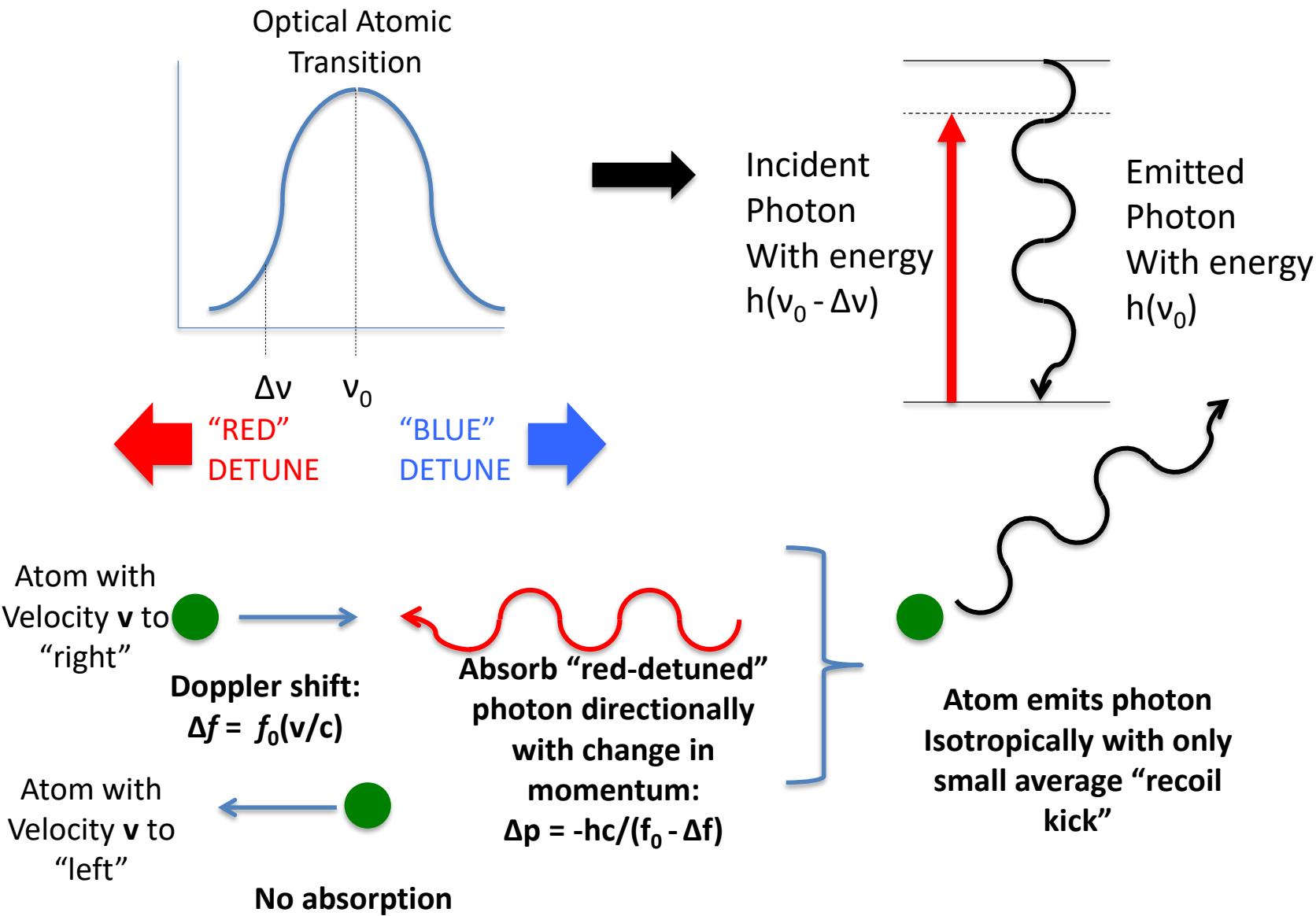
Short term stability: **typical:** $2e-13$ at 1 s, **best:** $1e-13$ at 1 s

Long term drift: **typical** $2e-15/\text{day}$, **best** $2e-16/\text{day}$

Sidebar: New Techniques

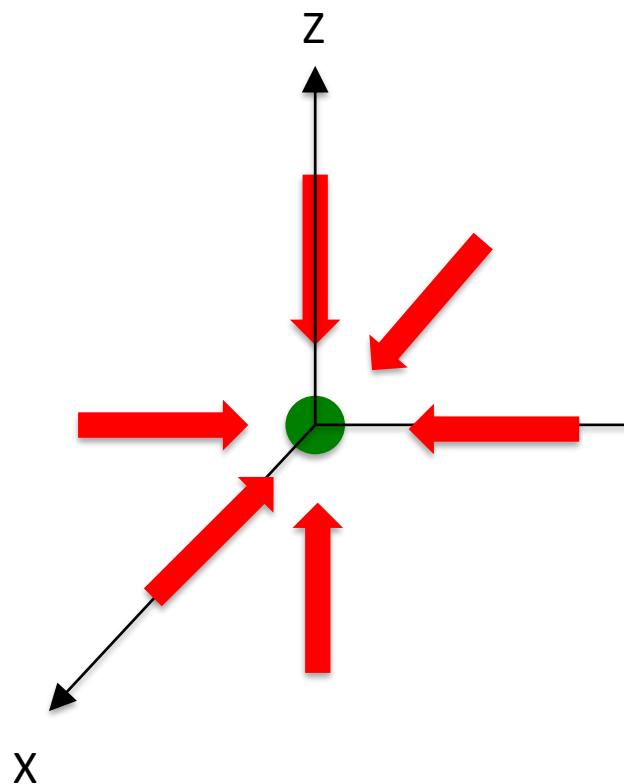
Side bar 1: Laser Cooling

How it works



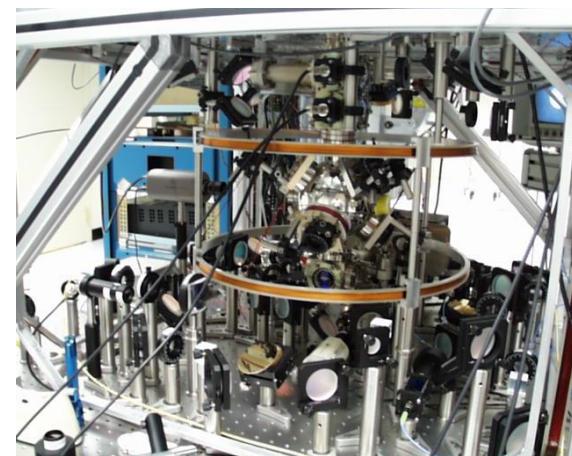
Side bar 1: Laser Cooling How it works

Now add “red-detuned” lasers in all three directions



ALL DIRECTIONS SLOWED BY LIGHT:
“OPTICAL MOLASSES”

Sub-Doppler cooling $\rightarrow \sim 1 \text{ } \mu\text{K}$
Average velocity $\sim 1 \text{ cm/s}$



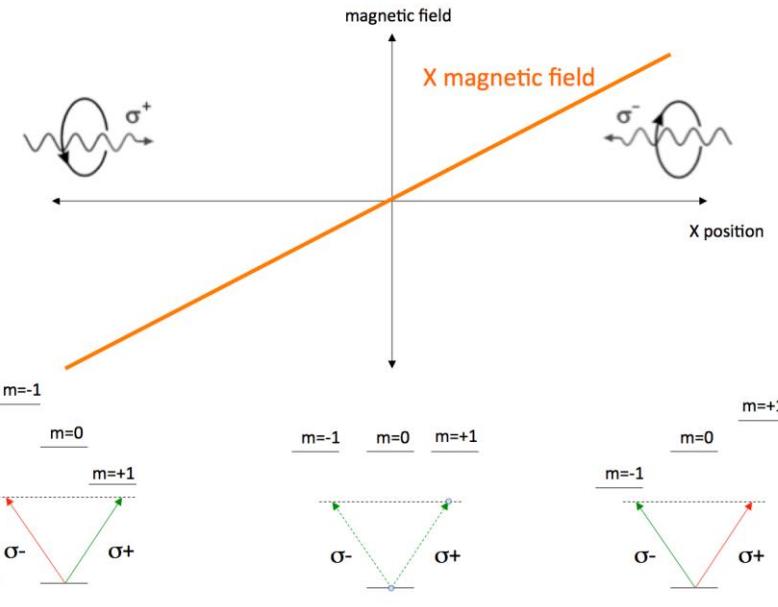
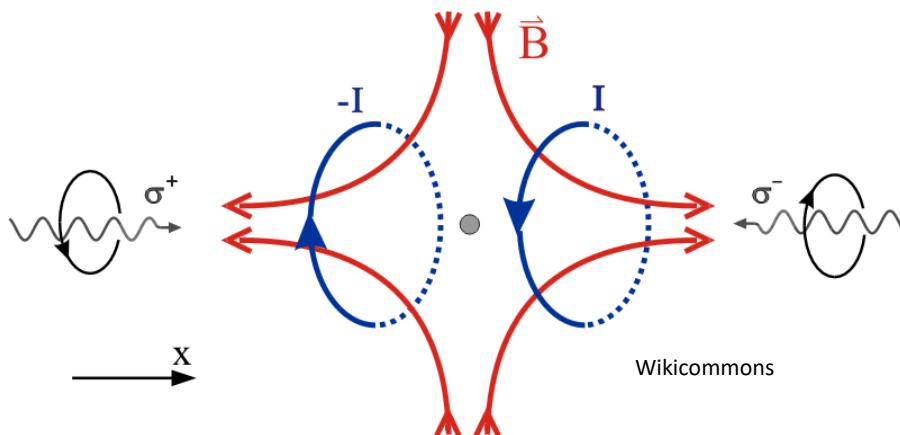
Side bar 1: Laser Cooling

Why it is useful for clocks

Atom confinement for O(s) instead of O(ms)

- Enables trapping and in-situ interrogation
 - Eliminate “end-to-end” effects
 - Trapping extends confinement indefinitely
 - very long interrogation times possible
- Enables moving atom ensembles over macroscopic distances
 - Atomic fountains

Side bar 2: Neutral Atom Trapping



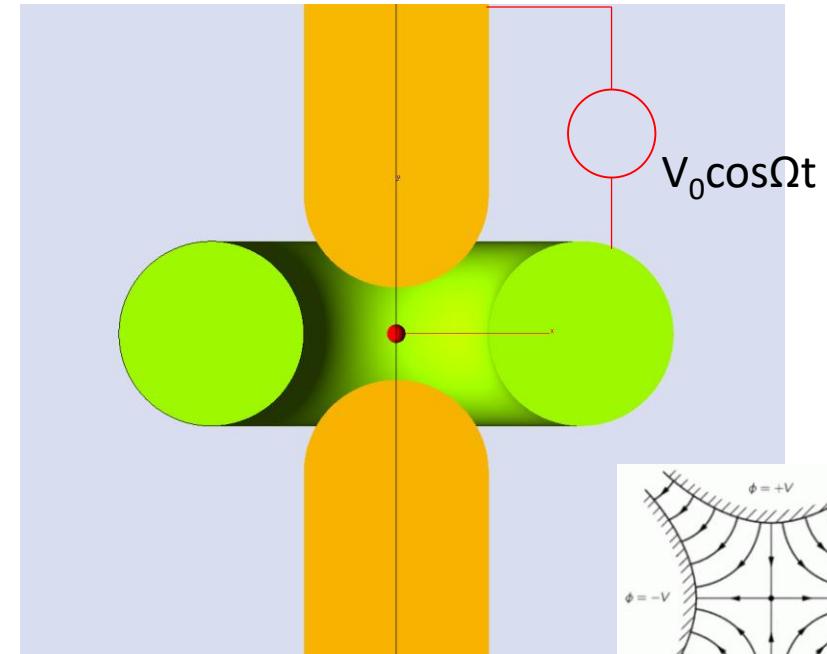
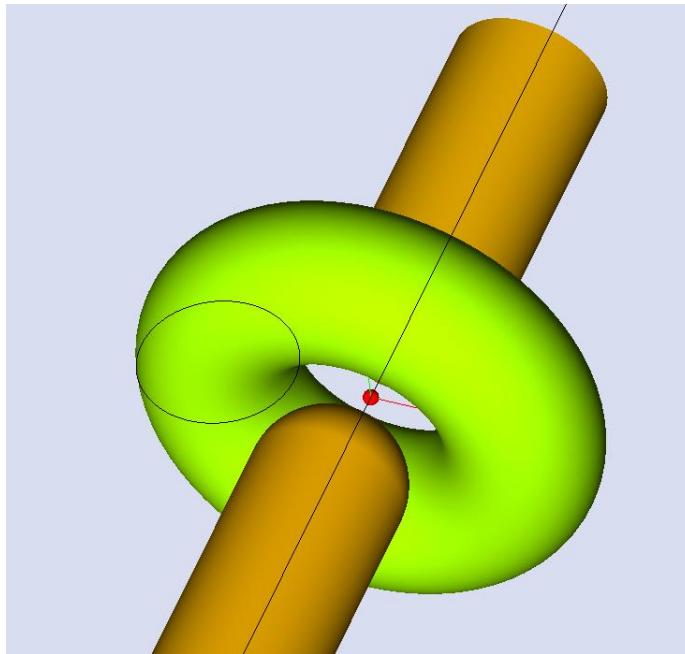
**Magnetic Field + Circularly Polarized Light
= Position-dependent restoring force
= Magneto-Optic Trap (MOT) !**

- Combine detuning and Zeeman shift to create a position-dependent restoring force
- Circular polarization drives $\Delta m = 1$ Zeeman transitions
- Strong field away from geometric center shifts transition into resonance with laser
 - \Rightarrow light pressure
- Weak field in center: laser off resonance – little or no interaction with atoms
- Atoms localized (and cooled) in 1D
- Extend to 3D: Magneto Optical Trap (MOT)

Side bar 3: Ion Trapping

The quadrupole Paul Trap

(Hans Dehmelt and Wolfgang Paul, Nobel Prize, 1989*)



Well Depth: $D = \frac{q_e V_0^2}{4m\Omega r_0^2}$

Typical: several eV

V_0 = rf amplitude (e.g., 300V)

m = ion mass (e.g., mercury 3.3×10^{-25} kg)

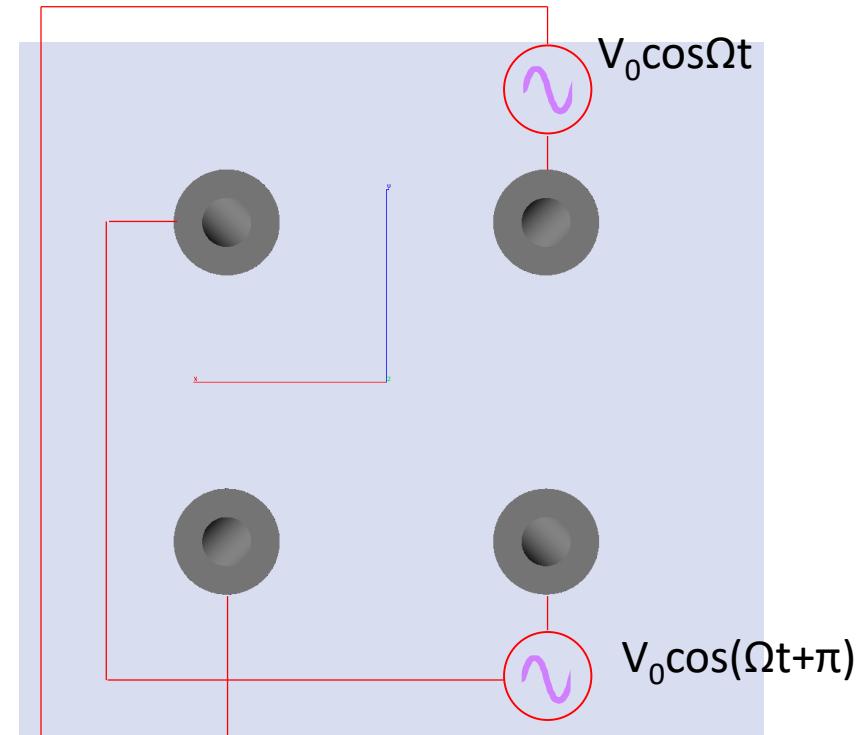
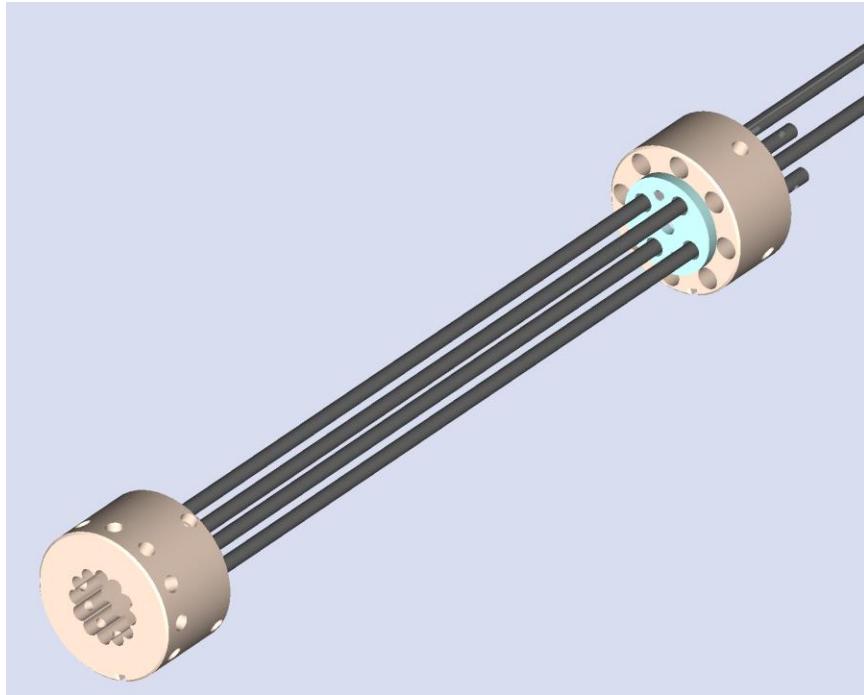
Ω = rf frequency (e.g., $2\pi \times 10$ MHz)

r_0 = ring inner radius (e.g., 1 mm)

*Normal Ramsey shared this Nobel prize for his invention of the method of separated oscillatory fields

Side bar 3: Ion Trapping

*The quadrupole linear ion trap**

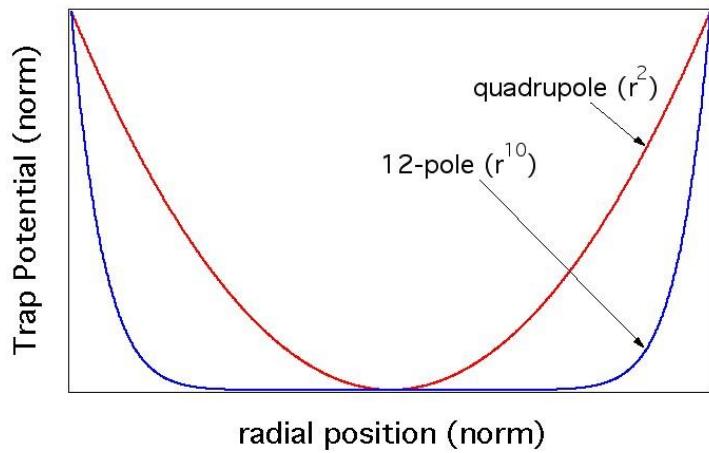
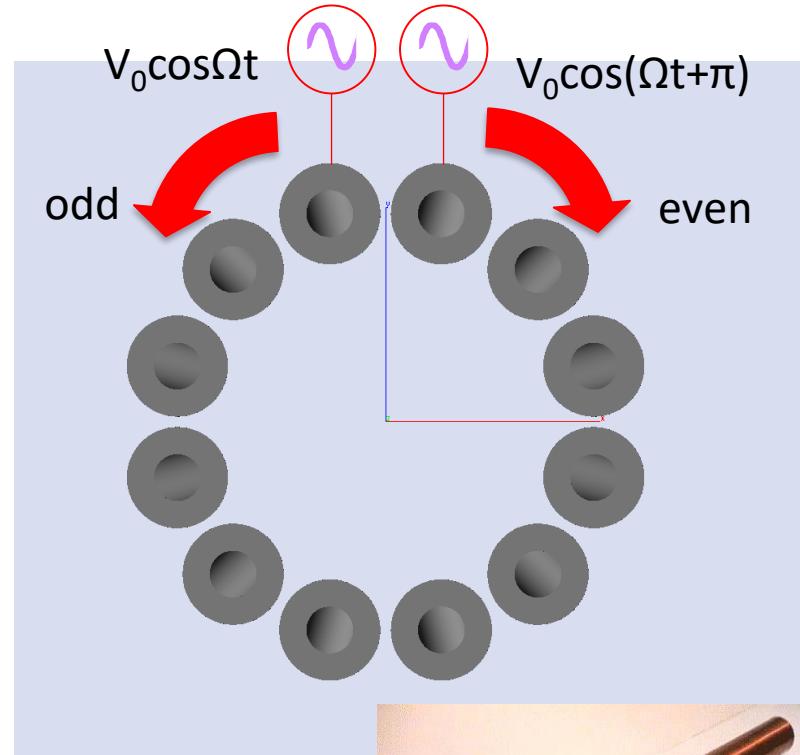
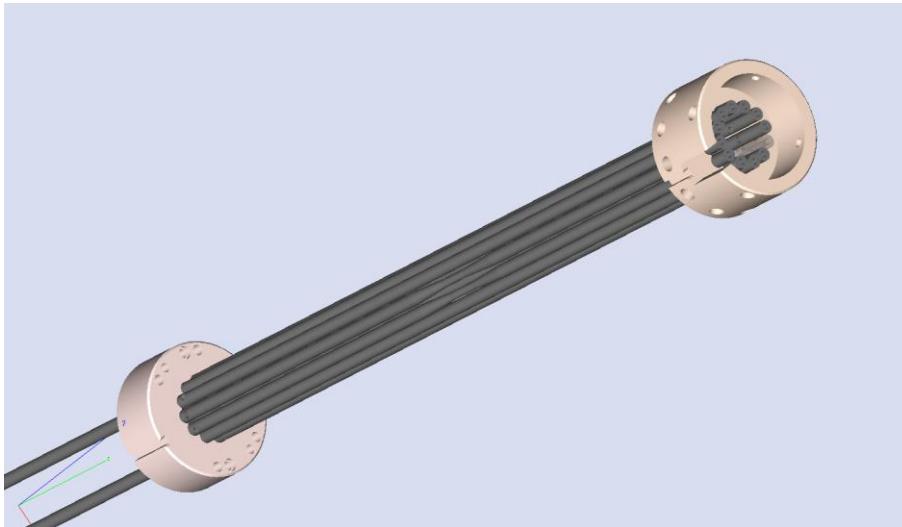


Number of ions scales up linearly

$$N_{lin} = \frac{3}{5} \left(\frac{L}{R_{sph}} \right) N_{sph}$$

Side bar 3: Ion Trapping

*The multipole linear ion trap**

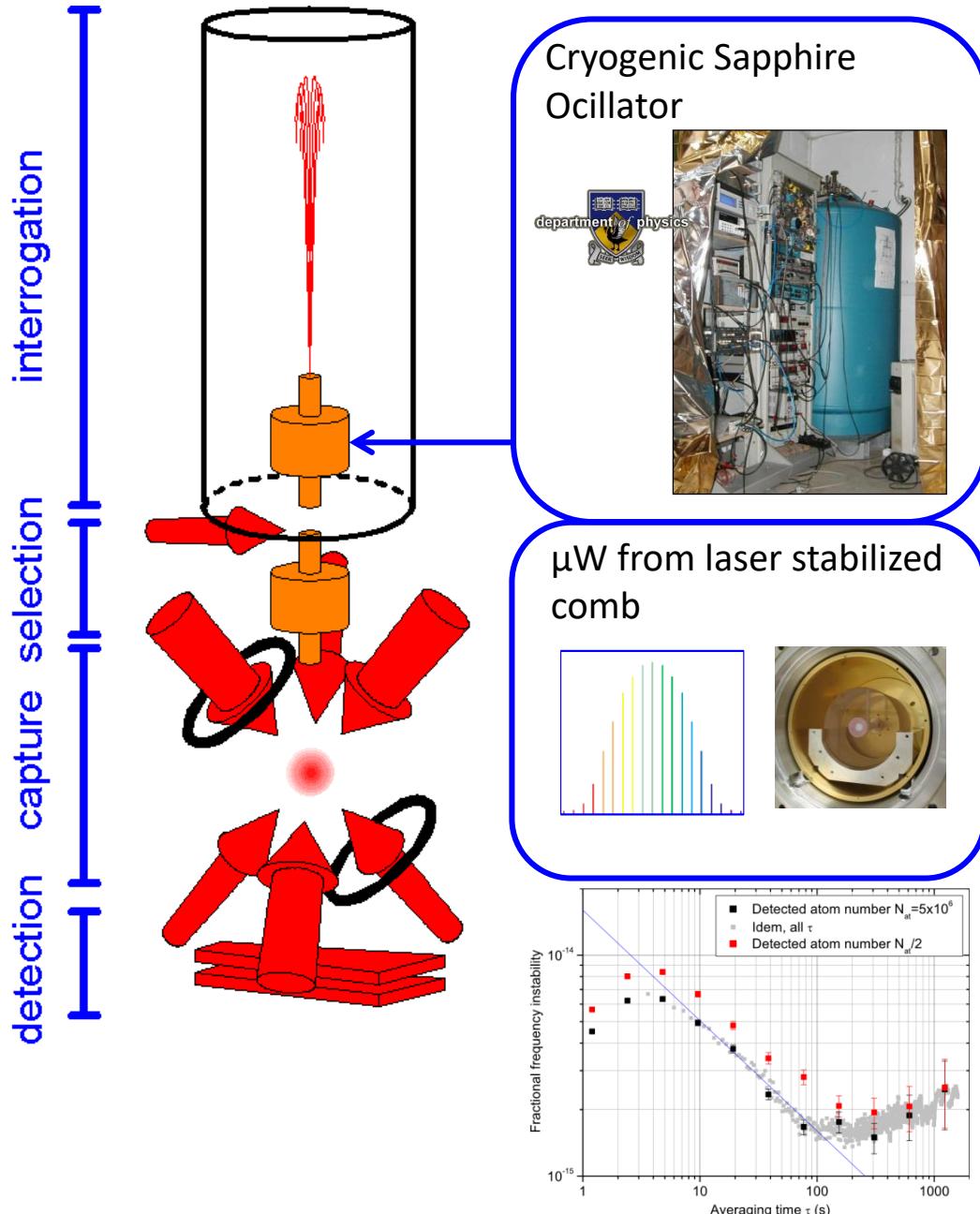


*J.D. Prestage, R. L. Tjoelker, and L. Maleki, Proc. 1997 IEEE IFCS (p. 225)

J.D. Prestage, R.L. Tjoelker, and L. Maleki, Proc. 1999 Joint EFTF and IEEE IFCS (p. 121)

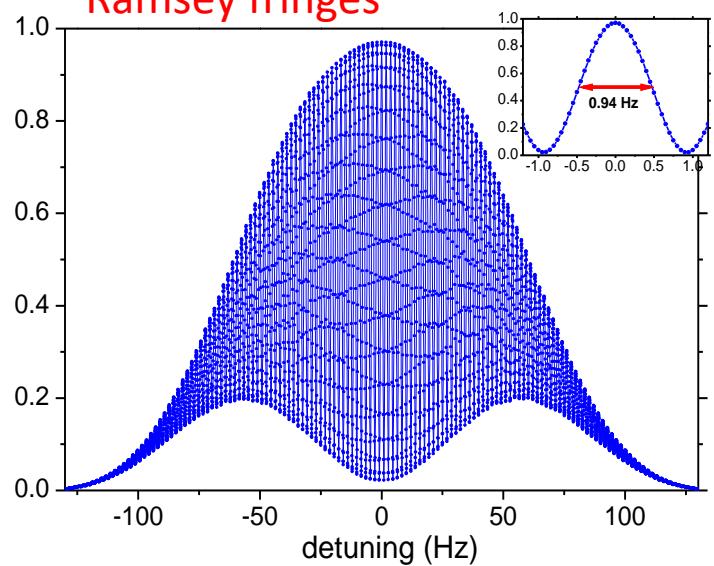
Microwave Atomic Clock Examples Part 2: The Cesium Fountain Clock

Atomic fountain clocks: concept



J. Guéna et al., IEEE TUFFC 59, 391 (2012)

Ramsey fringes



Atomic quality factor:

$$Q_{\text{at}} = \nu_{\text{ef}} / \Delta\nu \simeq 9.8 \times 10^9$$

Best frequency stability (Quantum Projection Noise limited): 1.6×10^{-14} @1s

$\Leftrightarrow \sigma_{\delta P} \sim 2 \times 10^{-4}$ in a single measurement (~ 1.6 s)

Best accuracy: $(2\text{-}3) \times 10^{-16}$

Atomic Fountain Clocks: Installations

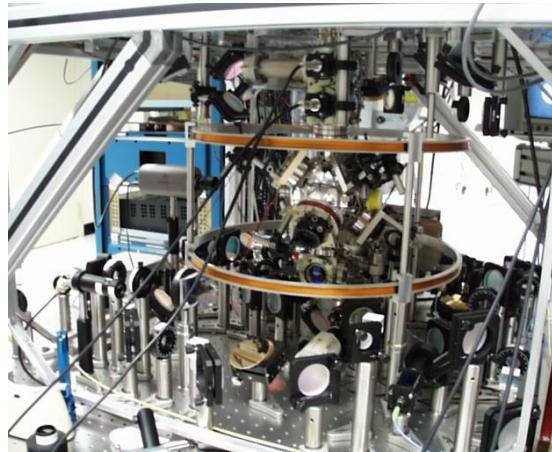
PRIMARY STANDARDS: Most national metrology labs, including:

- NIST (USA)
- NPL (UK)
- SYRTE (France)
- PTB (Germany)

CONTINUOUSLY RUNNING ENSEMBLES:

- USNO (USA)
- SYRTE (France)
- Others soon...

Atomic Fountain Clocks: Early research at USNO circa 1997

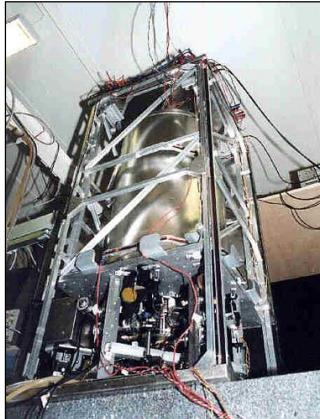


Atomic Fountain Clock Ensemble at SYRTE



FO1 fountain

^{133}Cs hfs



H-maser

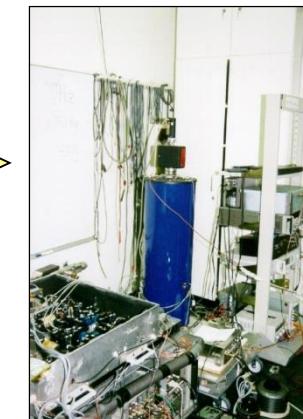


GPS
TWSTFT

NMIs &
BIPM

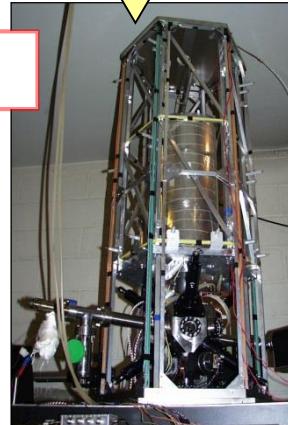
FOM transportable fountain

^{133}Cs hfs



FO2 dual fountain

$^{87}\text{Rb}, ^{133}\text{Cs}$ hfs



SYRTE fountain uncertainty budgets

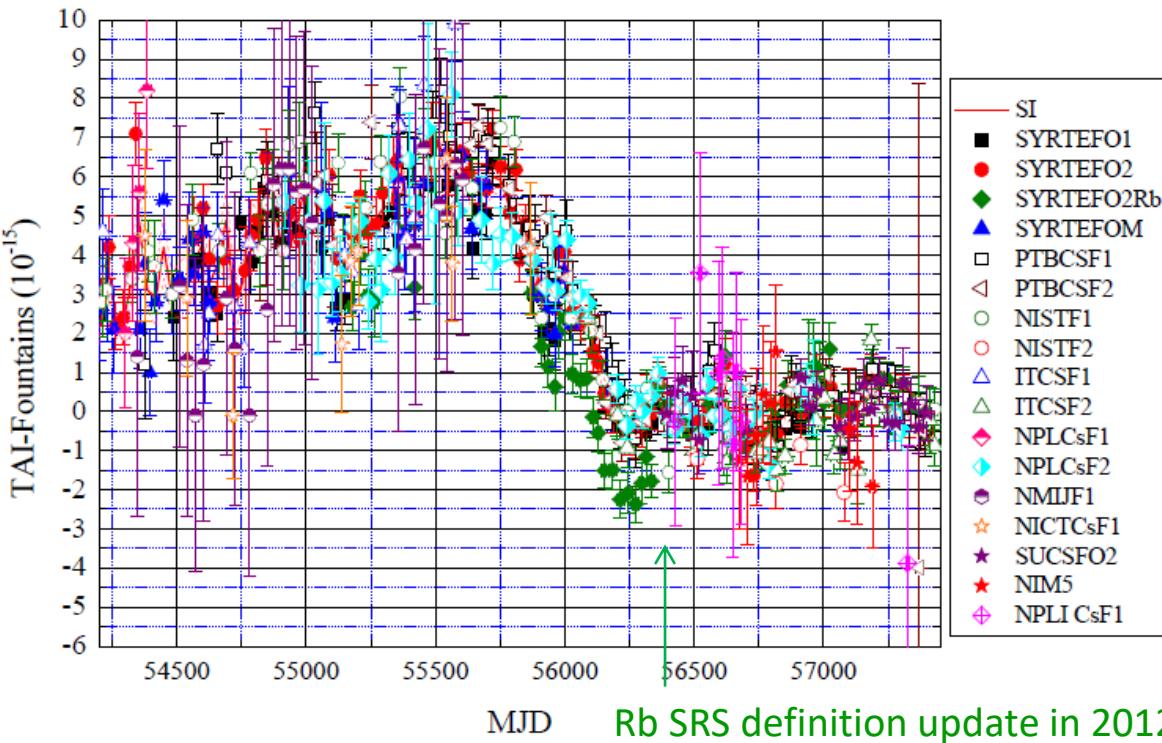
Unit 10^{-16}	FO1	FO2-Cs	FOM	FO2-Rb
Quadratic Zeeman Shift	-1274.5 ± 0.4	-1915.9 ± 0.3	-305.6 ± 1.2	-3465.5 ± 0.7
BlackBody Radiation	172.6 ± 0.6	168.0 ± 0.6	165.6 ± 0.6	122.8 ± 1.3
Collisions and Cavity Pulling	70.5 ± 1.4	112.0 ± 1.2	28.6 ± 5.0	2.0 ± 2.5
Distributed Cavity Phase Shift	-1.0 ± 2.7	-0.9 ± 0.9	-0.7 ± 1.6	0.4 ± 1.0
Spectral Purity and Leakage	<1.0	<0.5	<4.0	<0.5
Ramsey & Rabi pulling	<1.0	<0.1	<0.1	<0.1
Microwave Lensing	-0.7 ± 0.7	-0.7 ± 0.7	-0.9 ± 0.9	-0.7 ± 0.7
Second-Order Doppler Shift	<0.1	<0.1	<0.1	<0.1
Background Collisions	<0.3	<1.0	<1.0	<1.0
Total without Red Shift	1033.1 ± 3.5	-1637.5 ± 2.1	-113.0 ± 6.9	$-3341. \pm 3.3$
Red Shift	-69.3 ± 1.0	-65.4 ± 1.0	-68.7 ± 1.0	-65.4 ± 1.0
Total with Red Shift	-1102.4 ± 3.7	-1702.9 ± 2.3	-181.7 ± 6.9	-3406.4 ± 3.5

JG et al, IEEE TUFFC 59, 391 (2012)

- ▶ DCP shift *Phys. Rev. Lett.* 106, 130801 (2011)
- ▶ μ W lensing *arXiv:0403194v1, PRL* 97, 073002 (2006) *Metrologia* 48, 283 (2011)
- ▶ Background collisions *Phys. Rev. Lett.* 110, 180802 (2013)

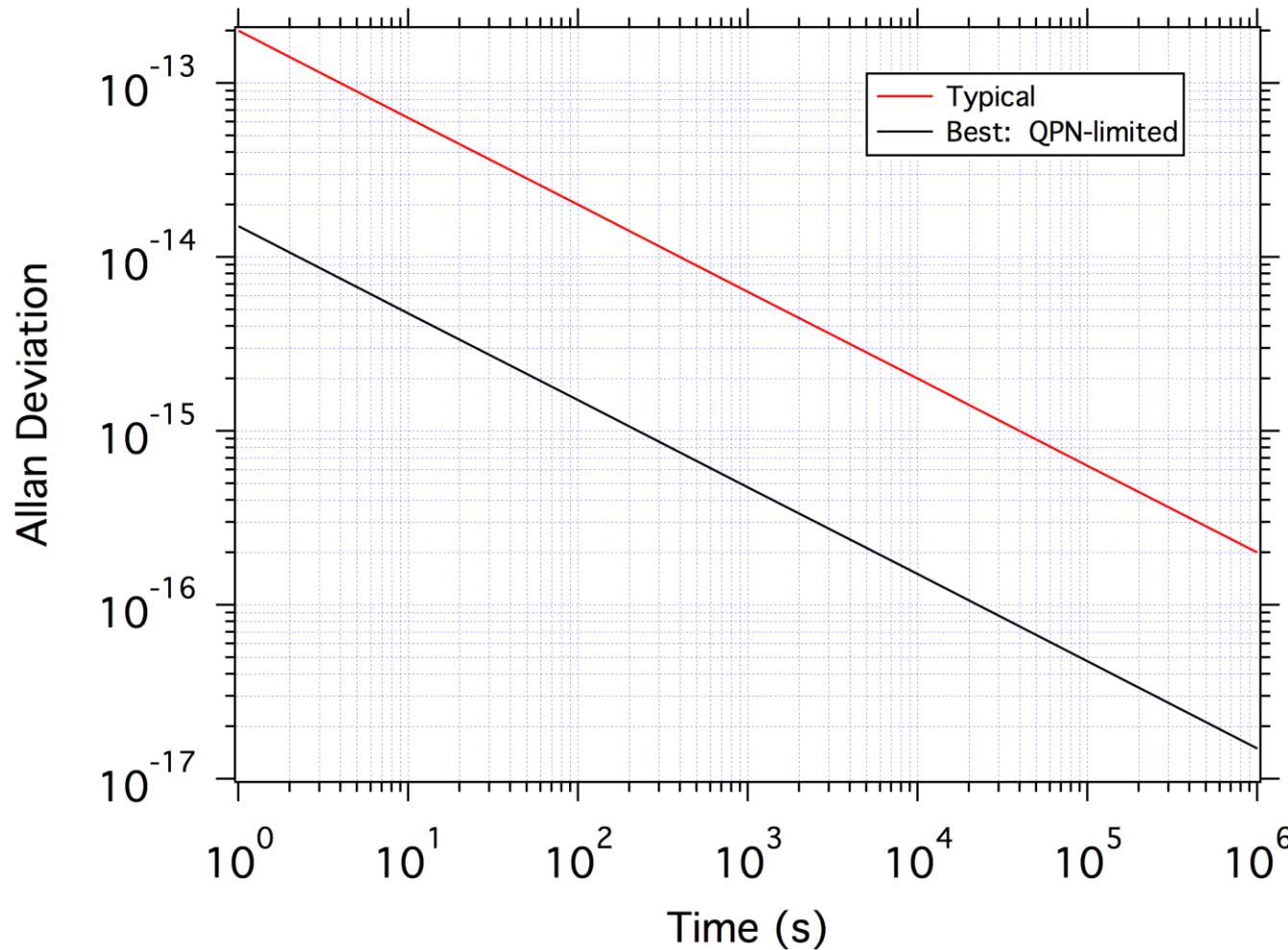
Contribution of SYRTE fountains to TAI

Data extracted from the BIPM *Circular T*



- Each month typically 4 to 6 Cs fountains over the world contribute to the accuracy of TAI with a calibration of a H-maser.
- About 40 to 50 % of the calibration were provided by the LNE-SYRTE fountains over the past 8 years
- Since 2012 FO2-Rb contribute as a secondary representation of the second and participate to the steering of TAI starting June 2013.

Atomic Fountains: Performance Summary



Short term stability: best: $1.5\text{e-}14/\sqrt{\tau}$, typical: $2\text{e-}13/\sqrt{\tau}$

Accuracy: $<4\text{e-}16$ (NIST, NPL, SYRTE, PTB)

Long term drift: $< 1\text{e-}18/\text{day}$ (USNO)

Microwave Atomic Clock Examples Part 3: Trapped Ion Clocks

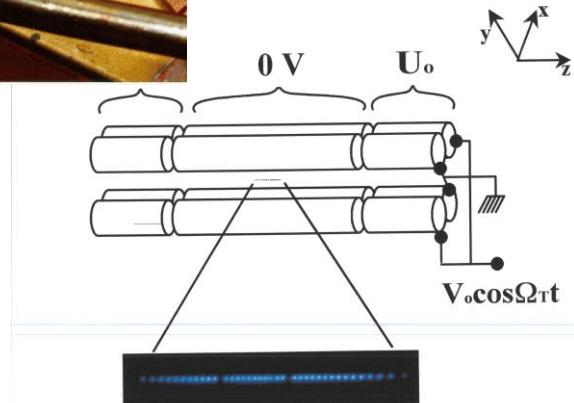
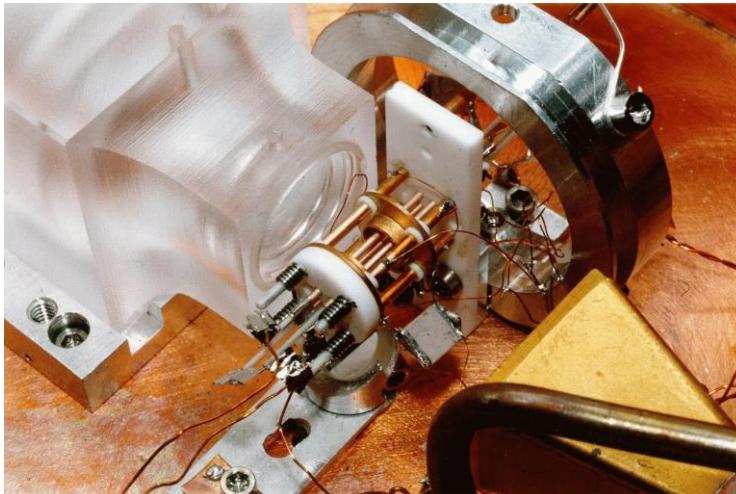
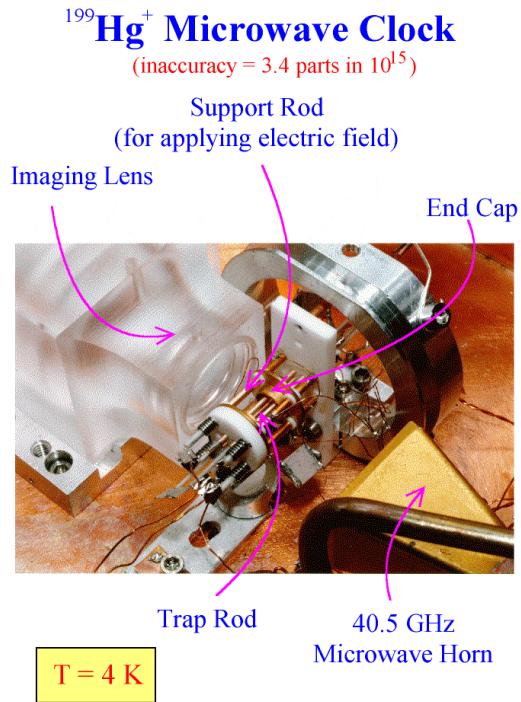
Trapped Ion Clocks

Two flavors:

- 1) Laser Cooled
- 2) Room Temperature

Trapped Ion Clocks: Laser Cooled

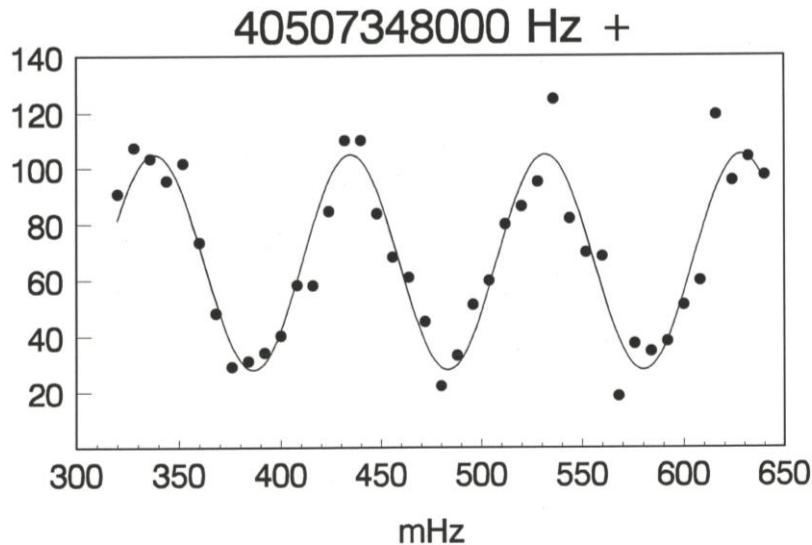
NIST laser-cooled trapped mercury ion clock



photos courtesy Jim Bergquist and Dave Wineland, NIST

Trapped Ion Clocks: Laser Cooled

NIST laser-cooled trapped mercury ion clock



Courtesy Jim Bergquist and Dave Wineland, NIST

- 10s Ramsey, 8 ions
- Achieved 3×10^{-15} accuracy and $3.3 \times 10^{-13} / \tau^{1/2}$ short-term stability*
- Comparable to laser-cooled fountains at the time
- Atomic line Q as good as 10^{13} using a 100 s Ramsey time (not shown)

Trapped Ion Clocks: Room Temperature (JPL)

Room Temperature Mercury Trapped Ion Clocks Overview

- **Long life, continuous, high stability operation**
 - Ultra-stable timekeeping & autonomy
 - Amenable to small, low power operation.
- **Mercury Ion Clock Paths and Applications :**

1. Ultra-Stable Performance¹ : UTC timescales

“Compensated” Multi-pole ion clock technologies:

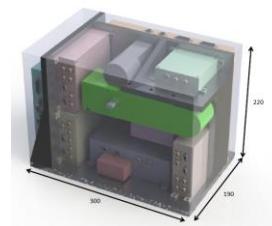
- 10^{-16} at 1 to 10 days, drift $\leq 10^{-17}/\text{day}$.
- 10^{-15} short term stability ($\sim 1 \text{ sec}$) via super LO's.



Ultra stable ion clock

2. Space: DSAC Technology Demonstration Mission² (TRL 5-7)

- Deep Space: 20W and 5 kg goal
- GNSS: 1×10^{-13} short term, 10^{-15} at 1 to 10 days
- Science and other apps....



MAFS & DSAC

3. Ultra-small, low power

- Few cm^3 ion trap³
- Miniature UV light sources⁴ and LO's



<10 cm³

¹E.A. Burt, W.A. Diener, and R.L. Tjoelker, IEEE TUFFC **55**, 2586 (2008)

²R.L. Tjoelker, et al., to be published in IEEE TUFFC

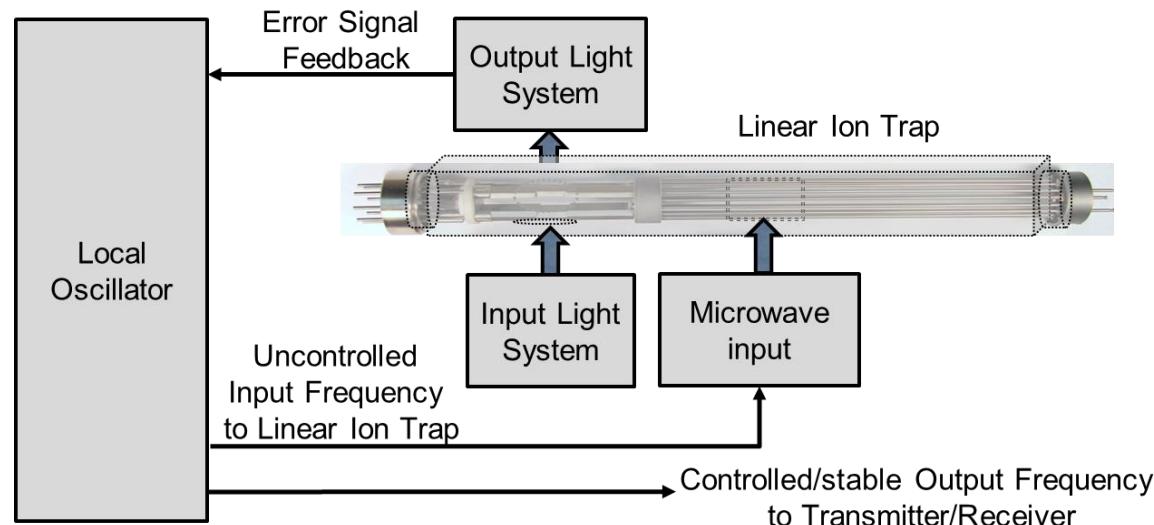
³J.D. Prestage, et al., PTTI (2013)

⁴L. Yi, et al., PTTI (2013)

Room Temperature Mercury Trapped Ion Clocks Overview

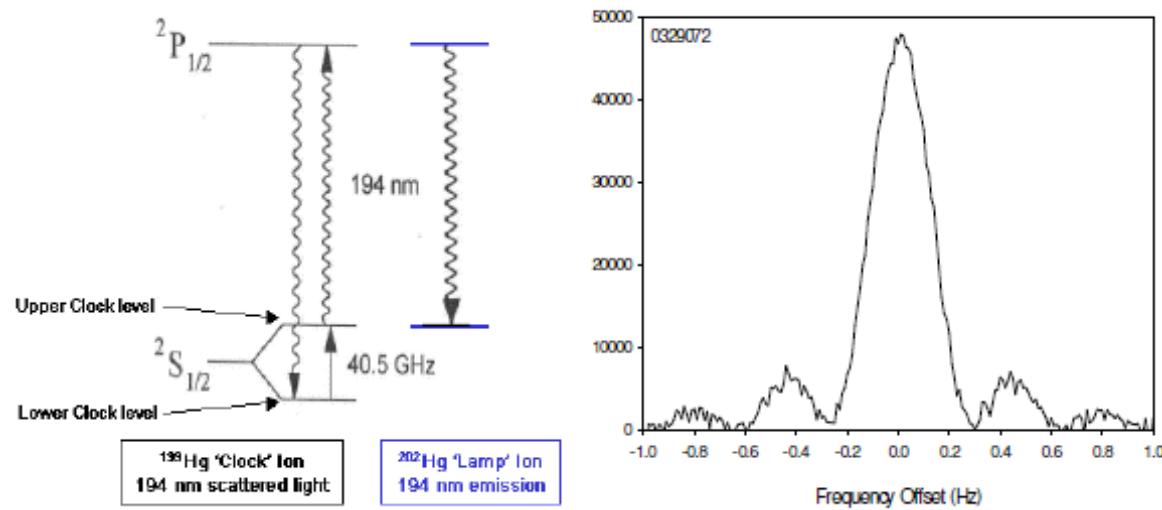
Key Performance Features:

- $10^6\text{-}10^7$ $^{199}\text{Hg}^+$ trapped ions
 - No wall collisions, high Q microwave line
 - buffer gas cooled to $\sim 300\text{K}$
 - multi-pole ion trap – *low T sensitivity*
- State selection:
 - Optical Pumping from $^{202}\text{Hg}^+$ lamp
 - 1-2 UV photons per second scattered
- High Clock Transition:
 - $40,507,347,996.8\text{ Hz}$ – *low B sensitivity*
- Adapts to variety of Local Oscillators – *flexible*



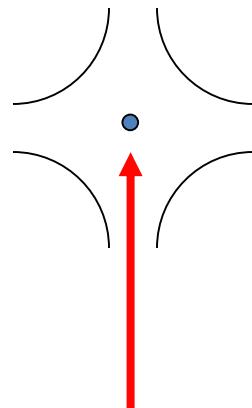
Key Reliability Features: - *practical*

- No Lasers
- No Cryogenics
- No Microwave cavity
- No Light Shift
- Low Consumables



The Multi-pole Ion Trap – A Comparison

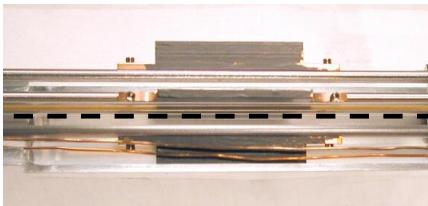
Spherical
Quadrupole
RF Trap



Field-free region at one point in center of trap

H.G. Dehmelt, Bull. Am.
Phys. Soc. 18, 1521 (1973)

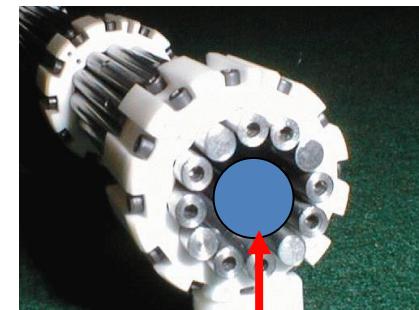
Linear
Quadrupole
RF Trap



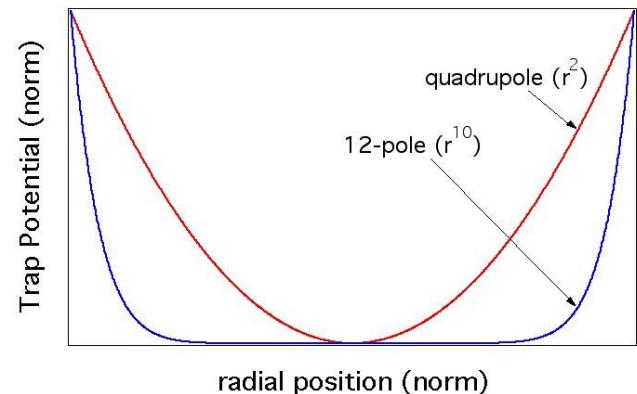
Field-free region on a line

J.D. Prestage, G.J. Dick,
and L. Maleki, J. Appl.
Phys. 66, 1013 (1989)

Multi-pole (12)
RF Trap



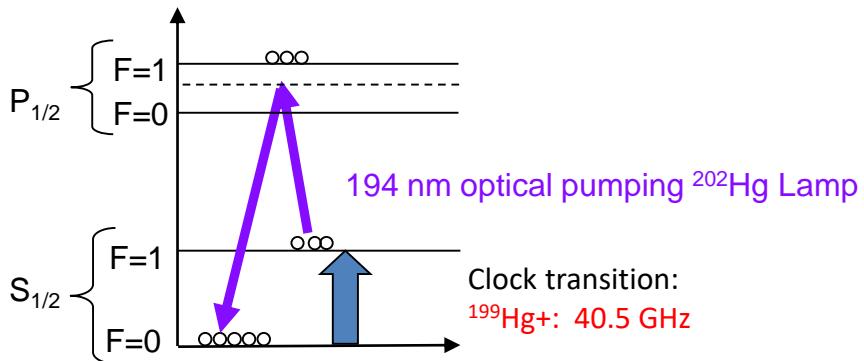
Field- "free"
Region in a volume



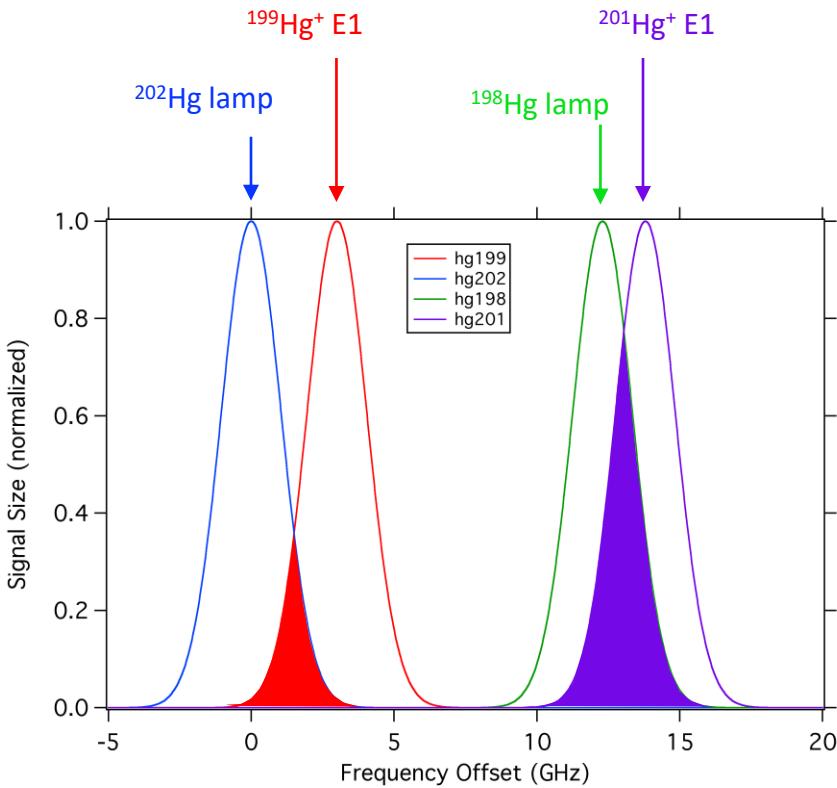
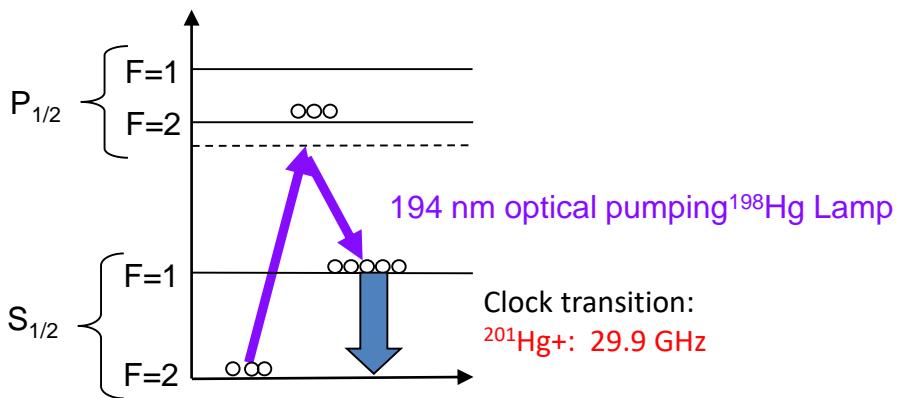
J.D. Prestage, R.L. Tjoelker,
and L. Maleki, Proceedings
of the 1999 Joint EFTF-FCS

Mercury Ion Energy Level Diagrams

$^{199}\text{Hg}^+$ energy level scheme

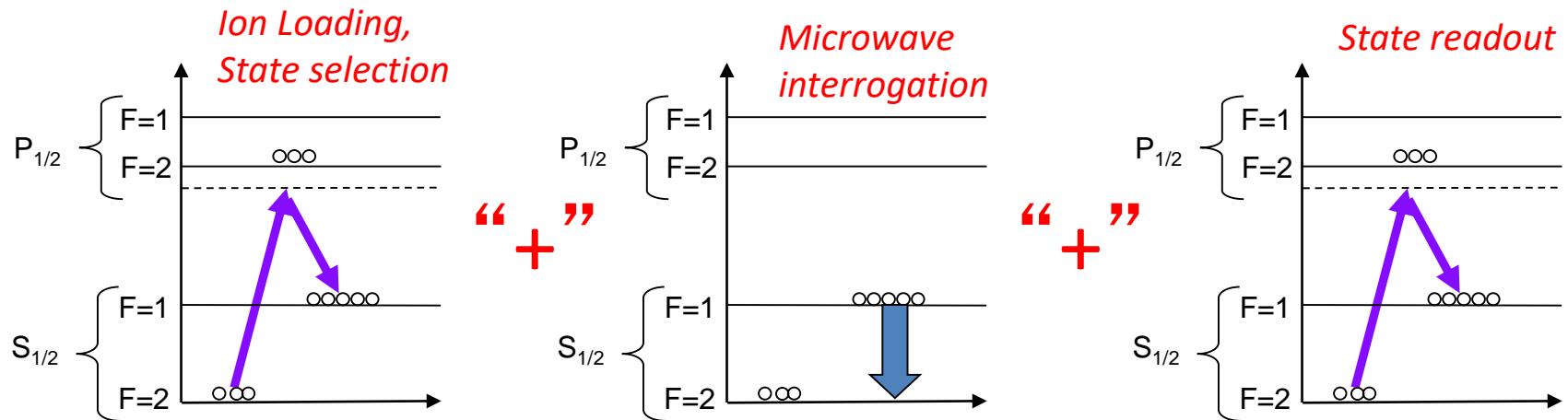


$^{201}\text{Hg}^+$ energy level scheme

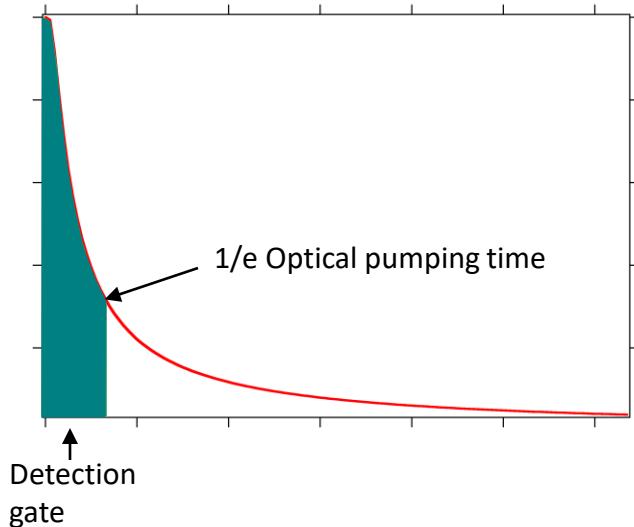


Better 198/201 overlap =>
 • possibly more signal
 • possibly faster OP

Mercury-199 Ion Normal Clock Operation

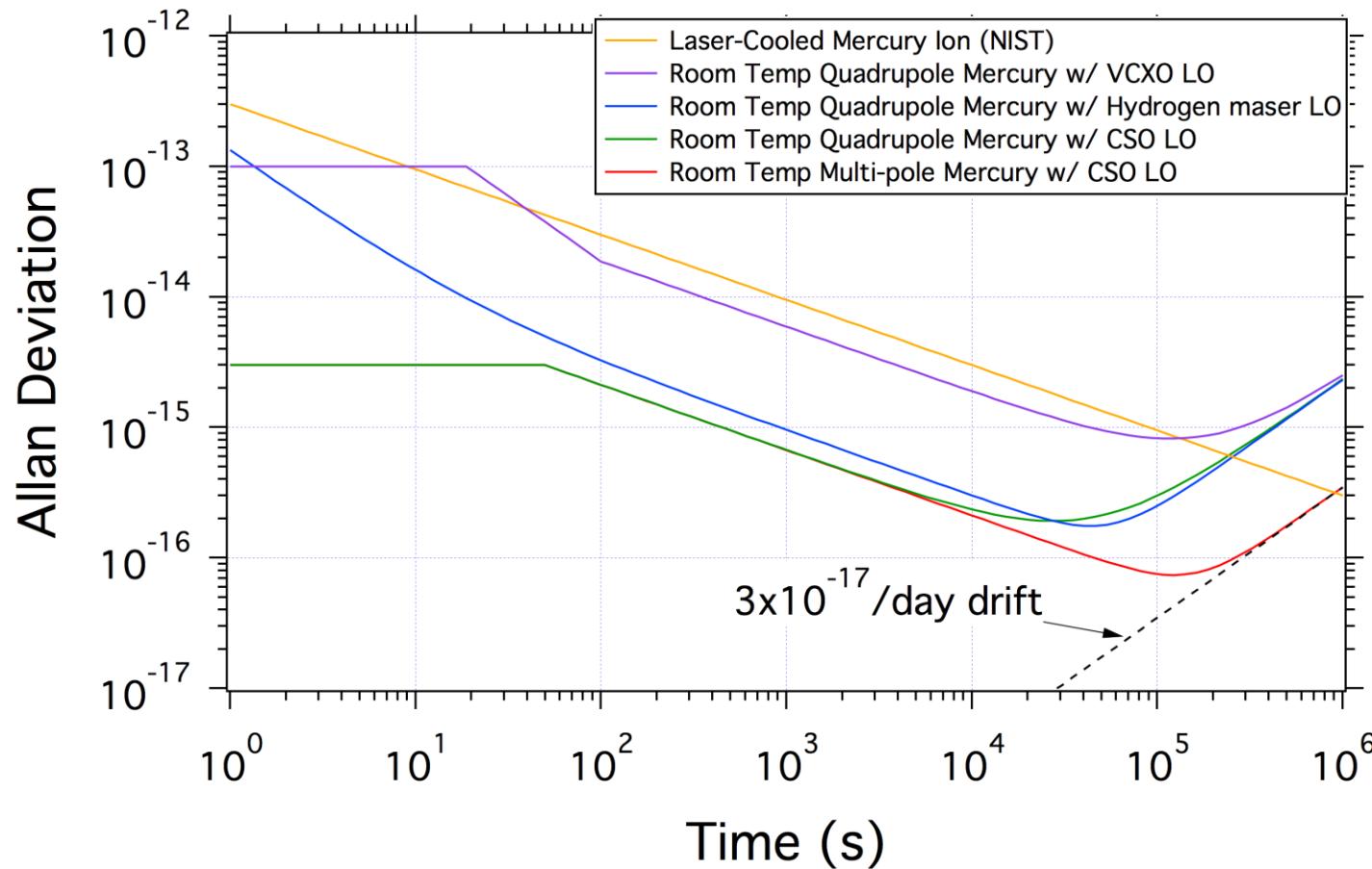


Detect decaying signal:



- Lamp off during microwave interrogation avoids light shift
- Detection gate = OP time: optimal SNR

Mercury Ion Clock Performance Summary



Short term stability: best: $2e-14/\sqrt{\tau}$, typical: $< 1e-13/\sqrt{\tau}$

Accuracy: $3e-15$ (NIST - 1998)

Long term drift: $< 3e-17/\text{day}$ (JPL)

Room Temperature Mercury Ion Clock Frequency: 40.5 GHz Sensitivities impacting long term stability (Secondary sensitivities enter through these)

1. Magnetic Shifts

- Shield external fluctuations
- Stable bias field

$$v = v_o + C_B B^2 \quad C_B \propto \frac{1}{v_o} \quad \frac{1}{v_o} \frac{\partial v}{\partial B} \propto \frac{B}{v_o^2}$$

2. Second-order Doppler Shifts

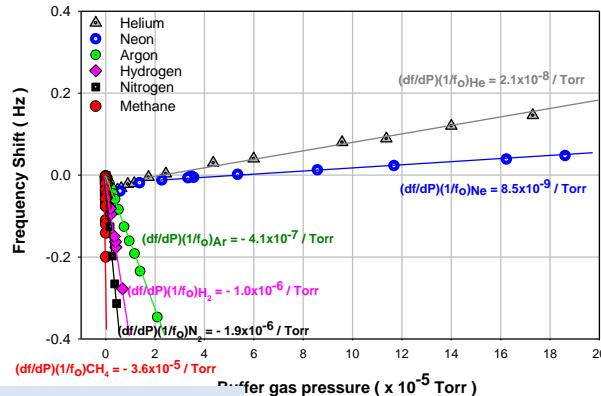
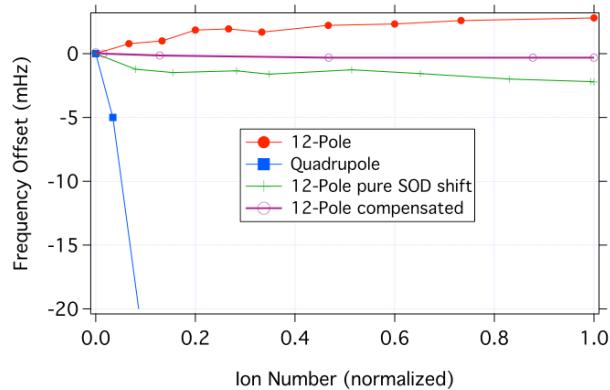
- Ion number/space charge & temperature variations
- Low sensitivity due to multi-pole ion trap design.

$$\frac{\Delta f}{f} = -\frac{3k_B T}{2mc^2} \left(1 + \frac{2}{3} N_d^{-k}\right) \quad N_d^{-k} = \frac{1}{k-1}.$$

3. Pressure/collision Shifts

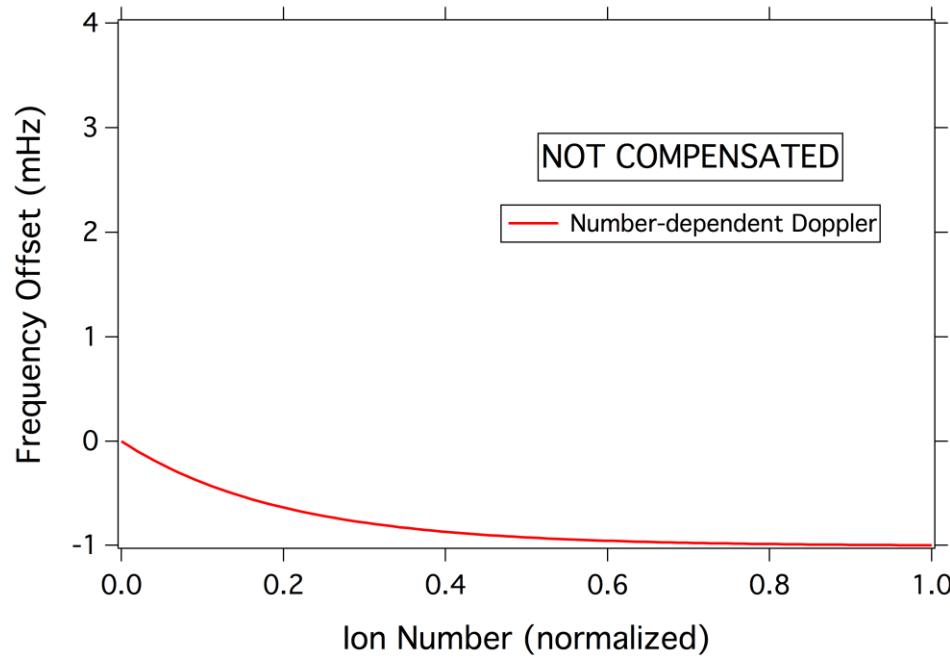
- Use low shifter for buffer gas (Neon).
- Reduce all other gasses via ultra high vacuum practices.
- Minimize time variability of trace gasses.

F_H	$1.4 \text{ GHz} + (2764 \text{ Hz/G}^2)B^2$
F_{Rb}	$6.8 \text{ GHz} + (574 \text{ Hz/G}^2)B^2$
F_{Cs}	$9.2 \text{ GHz} + (427 \text{ Hz/G}^2)B^2$
F_{Hg+}	$40.5 \text{ GHz} + (97 \text{ Hz/G}^2)B^2$



Achievable long term stability depends on the specific implementation

Achieving Ultra-Stability in Room Temperature Ion Clocks: Magnetic Compensation

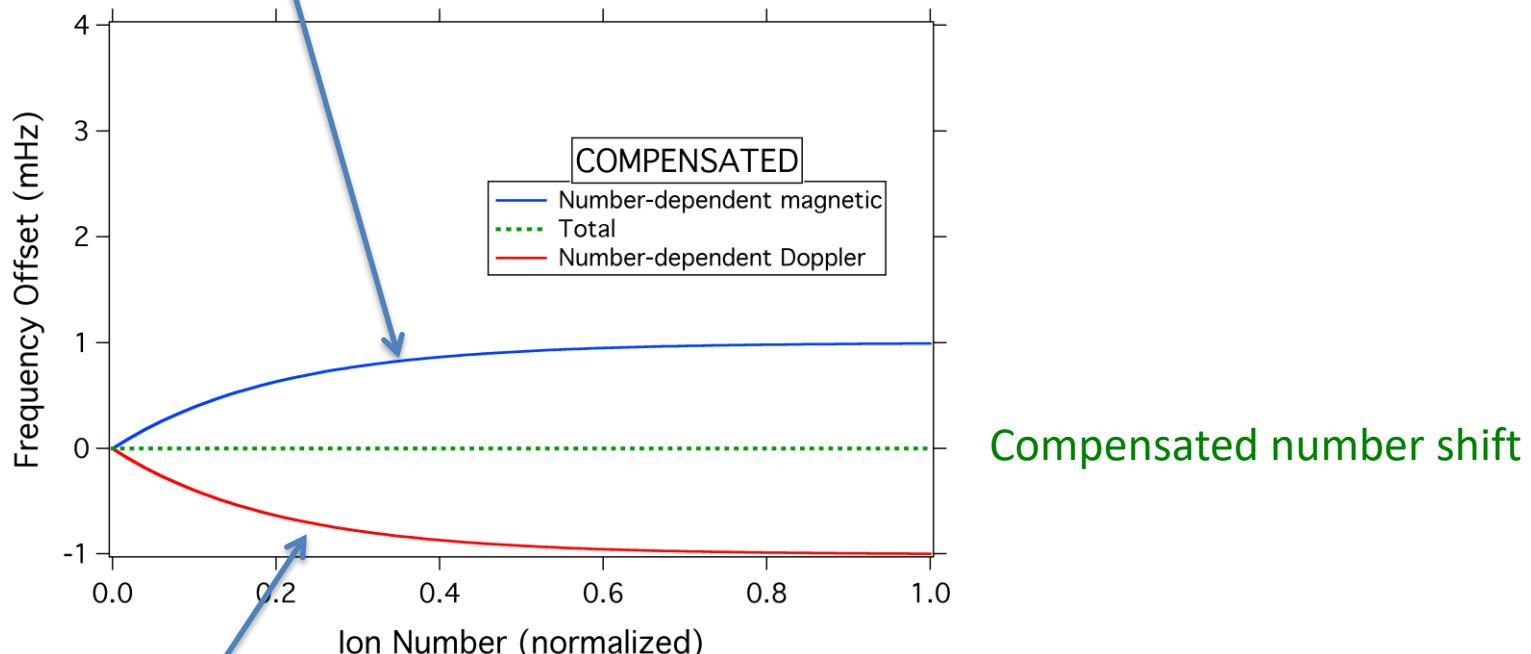


Second order Doppler shift $\left(\frac{df}{f}\right)_{TSOD} = -\frac{3k_B T}{2mc^2} \left(1 + \frac{2/3}{k-1}\right)$

Ultra-Stability using Magnetic Compensation

Second order Zeeman shift (Briet-Rabi)

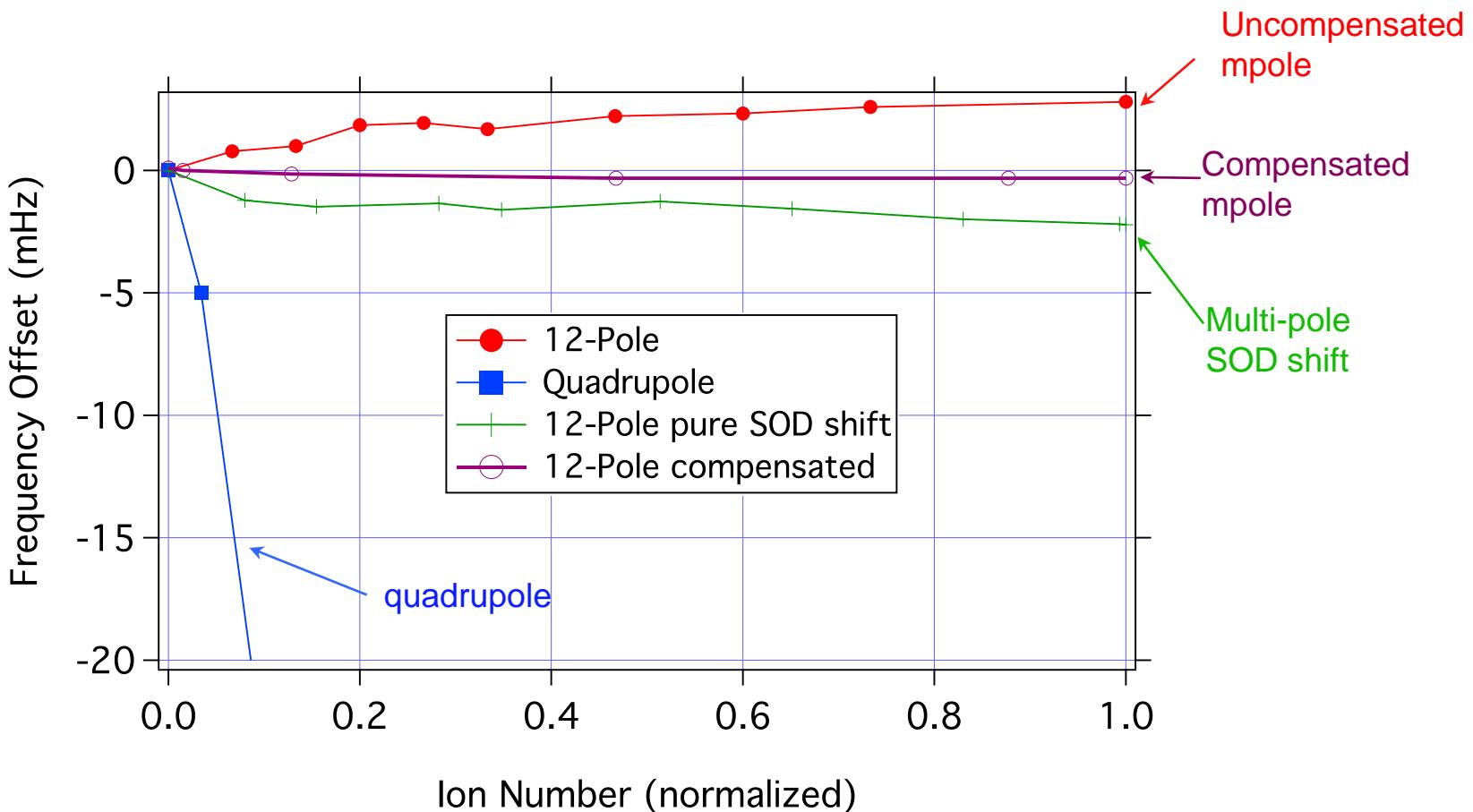
$$\left(\frac{df}{f}\right)_{SOZ} = -\frac{A}{2} \sqrt{1 + \left(\frac{2\mu_B B}{hA}\right)^2}$$



Second order Doppler shift

$$\left(\frac{df}{f}\right)_{TSOD} = -\frac{3k_B T}{2mc^2} \left(1 + \frac{2/3}{k-1}\right)$$

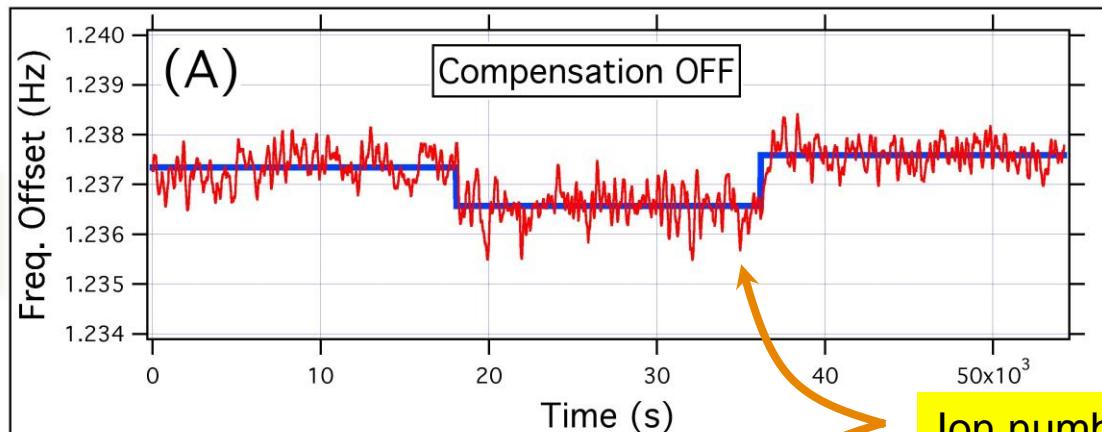
Long-Term Performance of LITS-9: Magnetic Compensation



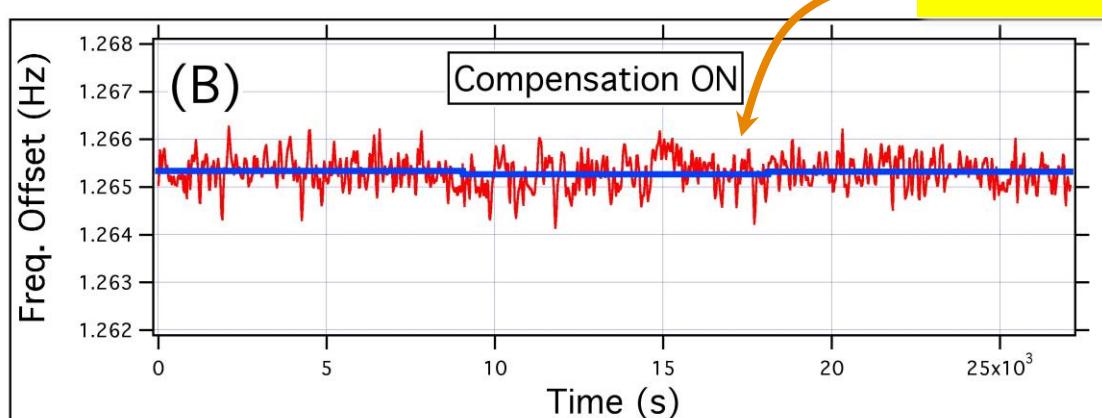
Sensitivity to ion number $< 5 \times 10^{-17}$
1% change: $< 1 \text{e-}18$

Long-Term Performance of LITS-9: Magnetic Compensation

$$\Delta f = -950(26) \mu\text{Hz} \\ = 2.3 \times 10^{-14}$$

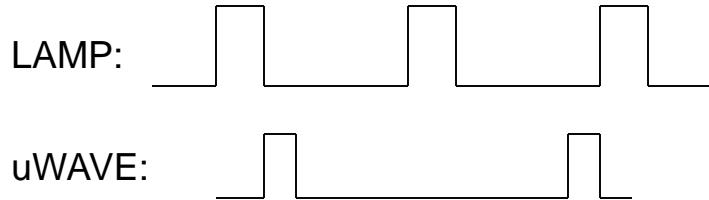


$$\Delta f = -64(19) \mu\text{Hz} \\ = 1.6 \times 10^{-15}$$

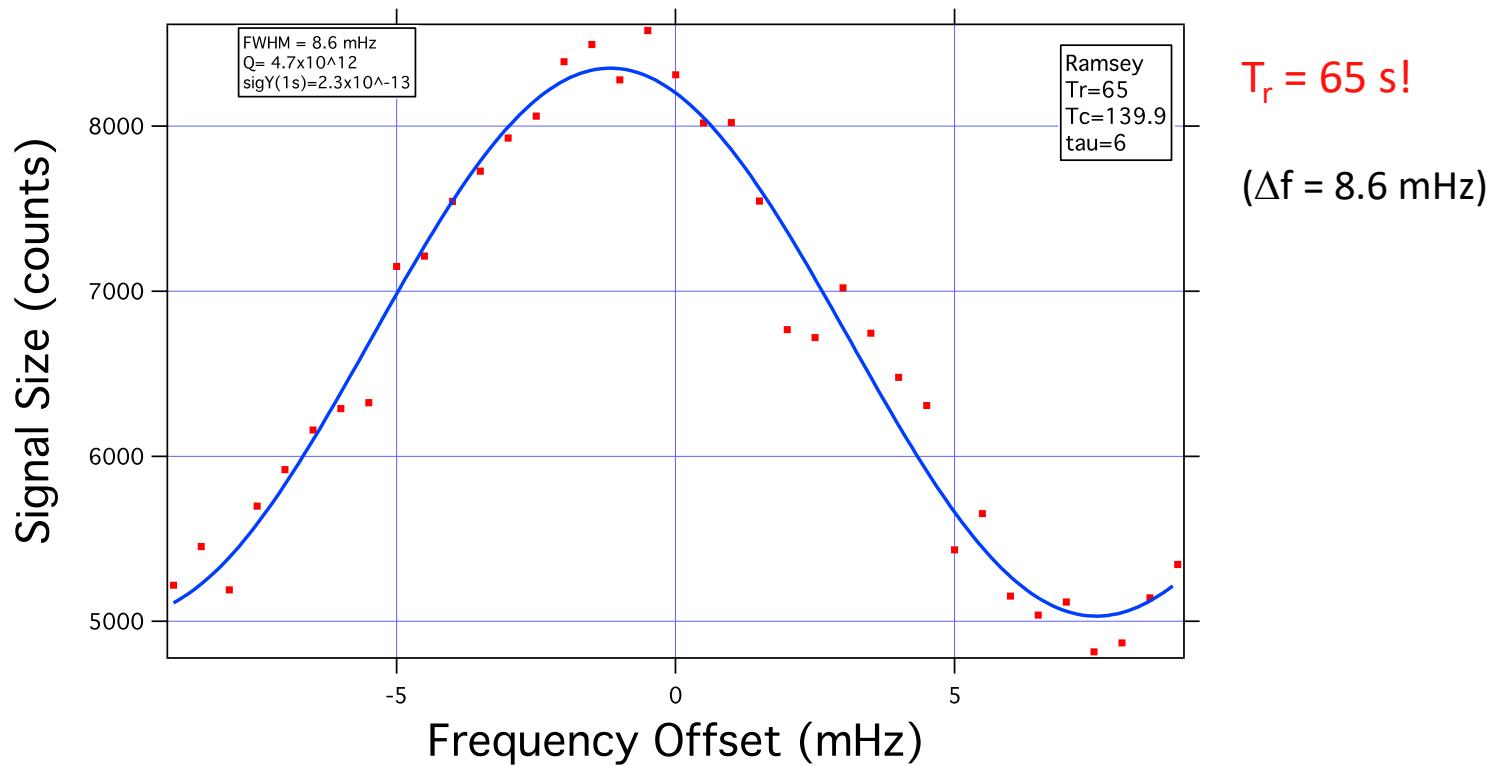


Compensation gives 15x reduction in sensitivity

LITS-9: Record Q



New lamp operational method:
• record line Q for LITS: 4.7×10^{12}
• second highest Q ever recorded
for a microwave standard



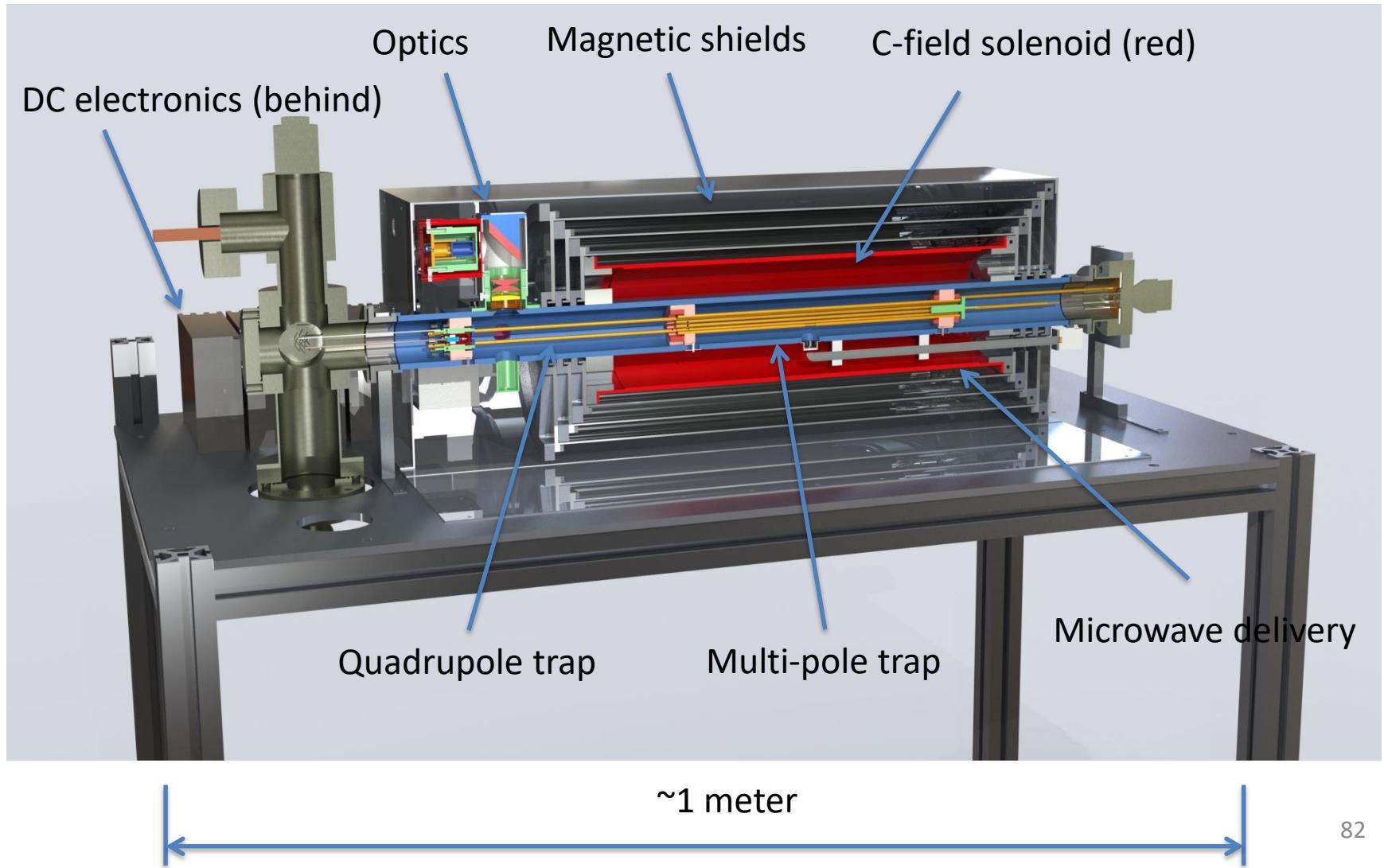
Stability Evaluation: what determines small residual instability??

Effect	Sensitivity	Units	Change	$\Delta f/f$ ($\times 10^{-17}/\text{day}$)	Uncertainty ($\times 10^{-17}/\text{day}$)
Temperature-dependent second-order Doppler shift	$+1.1(2.2)\times 10^{-8}$	torr^{-1}	$-3.6(0.9)\times 10^{-7}$ torr	-1.5	3.4
Collision shift due to neon buffer gas	$+8.5(1.7)\times 10^{-9}$	torr^{-1}	$-3.6(0.9)\times 10^{-7}$ torr	-1.1	0.6
Collision shift due to other background gas (CH ₄ dominates)	-3.6×10^{-5}	torr^{-1}	$<\pm 7.1\times 10^{-11}$ torr	--	0.94
Number-dependent second-order Doppler shift	$+7.1(0.8)\times 10^{-15}$	$(\Delta N/N)^{-1}$	-0.32(.05)	-0.84	0.23

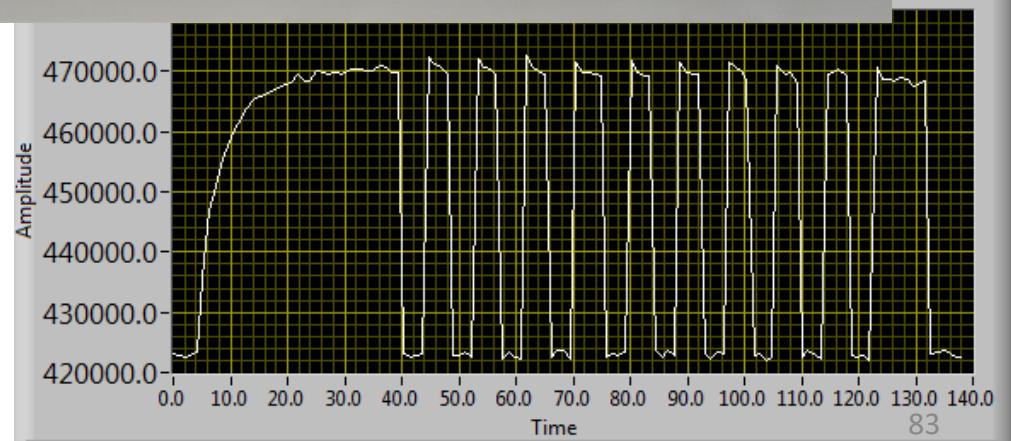
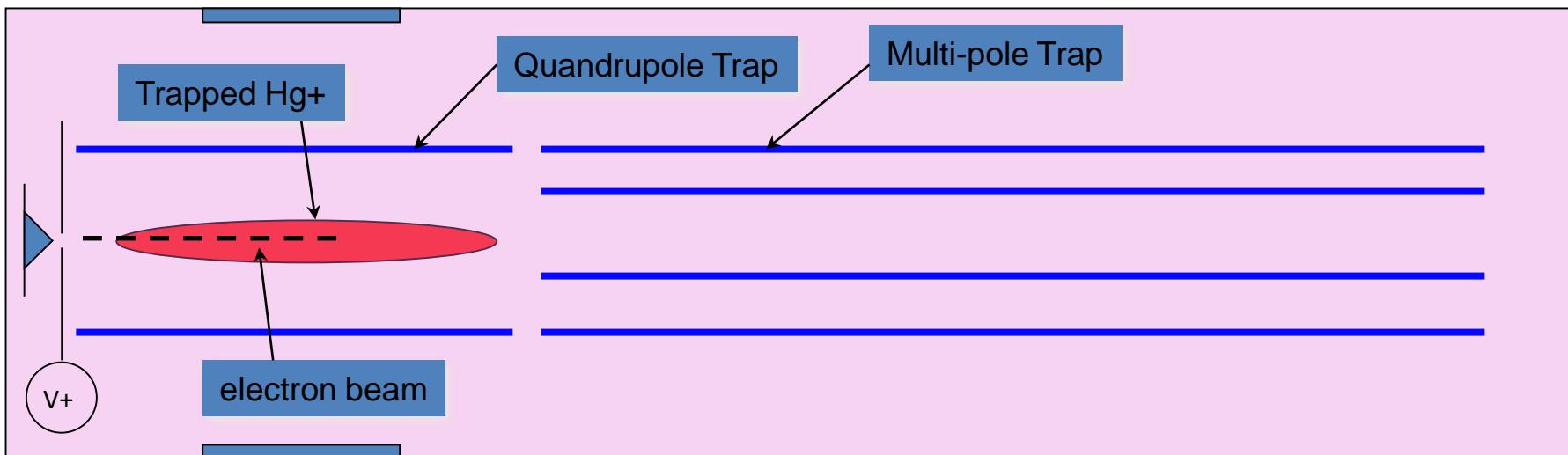


Improve Vacuum

L10 Design



Quadrupole to Multi-pole Transfer Efficiency

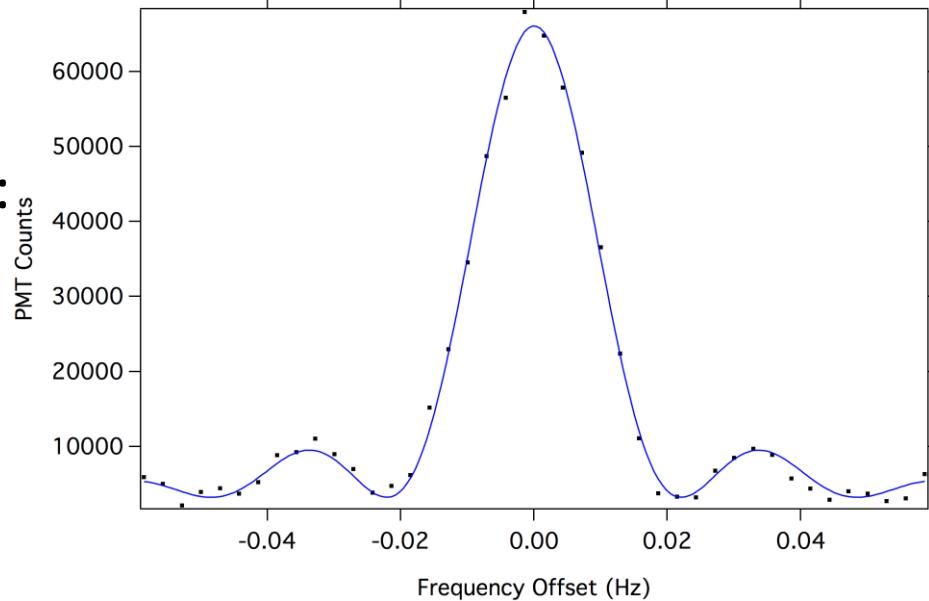


Short Term Clock Performance

Clock Transition Spectroscopy:

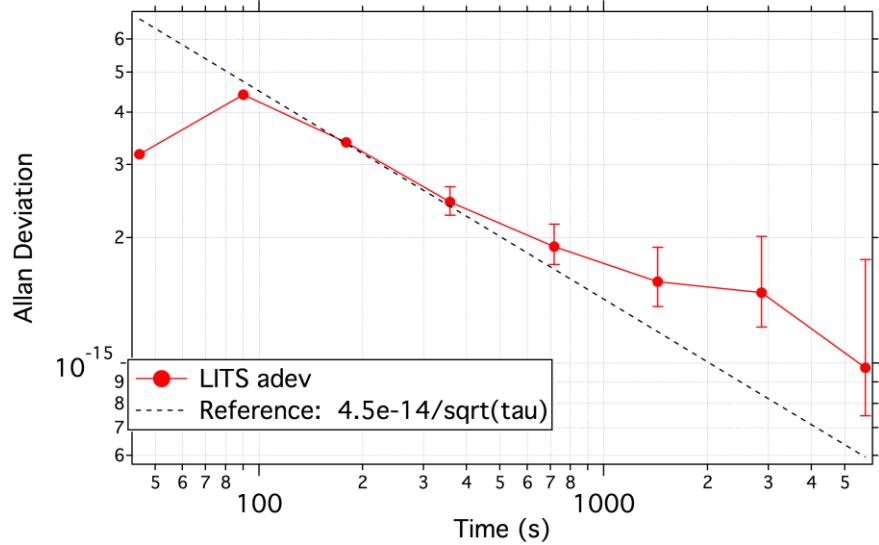
Here:

- Peak SNR ~ 70
- $\text{SNR}^*Q < 4 \times 10^{-14}/\sqrt{\tau}$

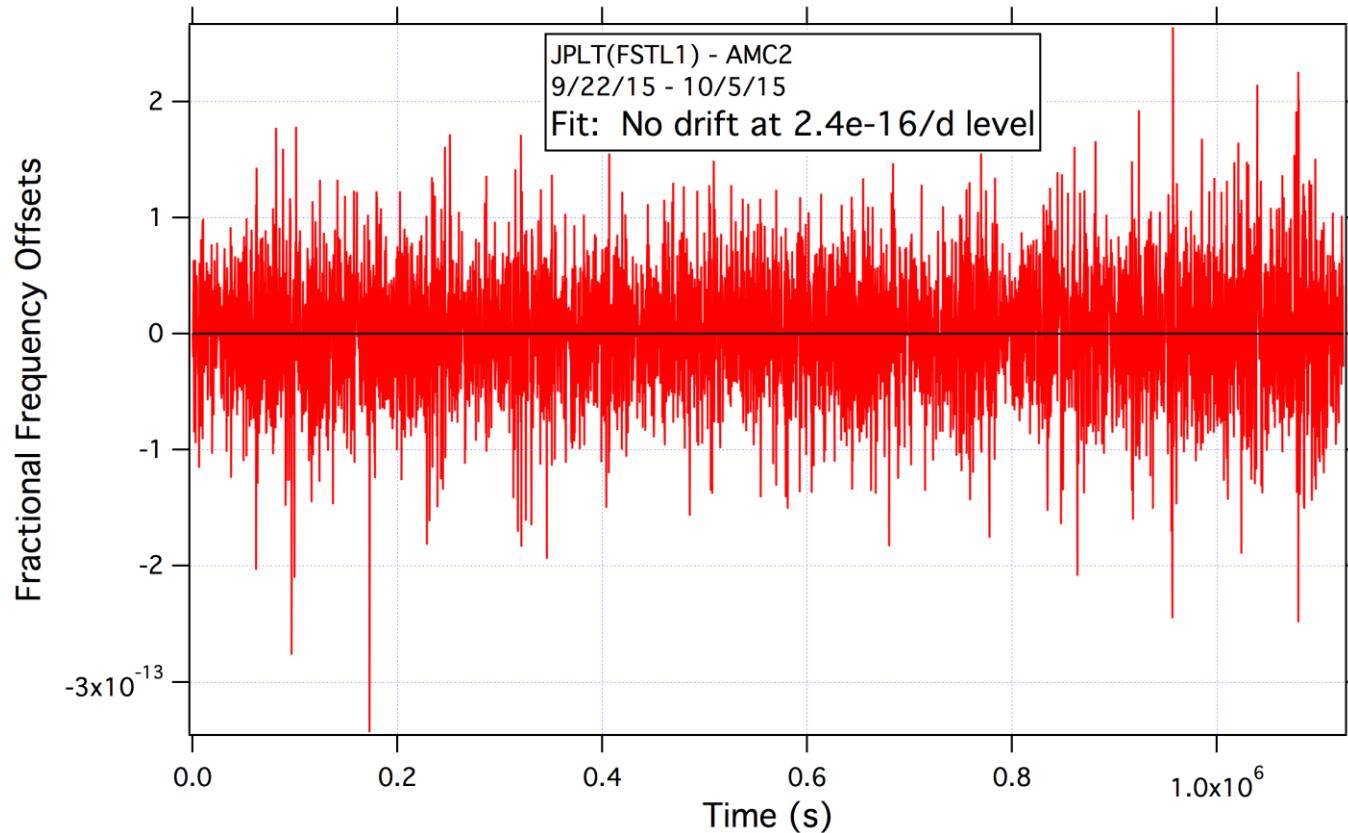


Initial short term stability

- $4.5 \times 10^{-14}/\sqrt{\tau}$
- $T=40\text{s}$



Initial FSTL1 Long-Term Performance: comparison to UTC(USNO)



- GPS CP Time transfer
- Sealed vacuum
- **No observed drift at 2.4×10^{-16} /day level**

Microwave Atomic Clock Applications

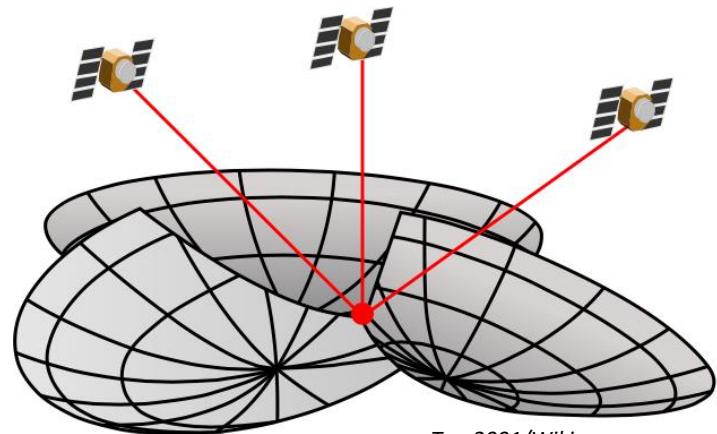
Microwave Atomic Clock Applications

- GPS
- Deep Space Navigation
- Fundamental Physics

Microwave Atomic Clock Applications: GPS



Wikicommons



Trex2001/Wikicommons



©Microsemi

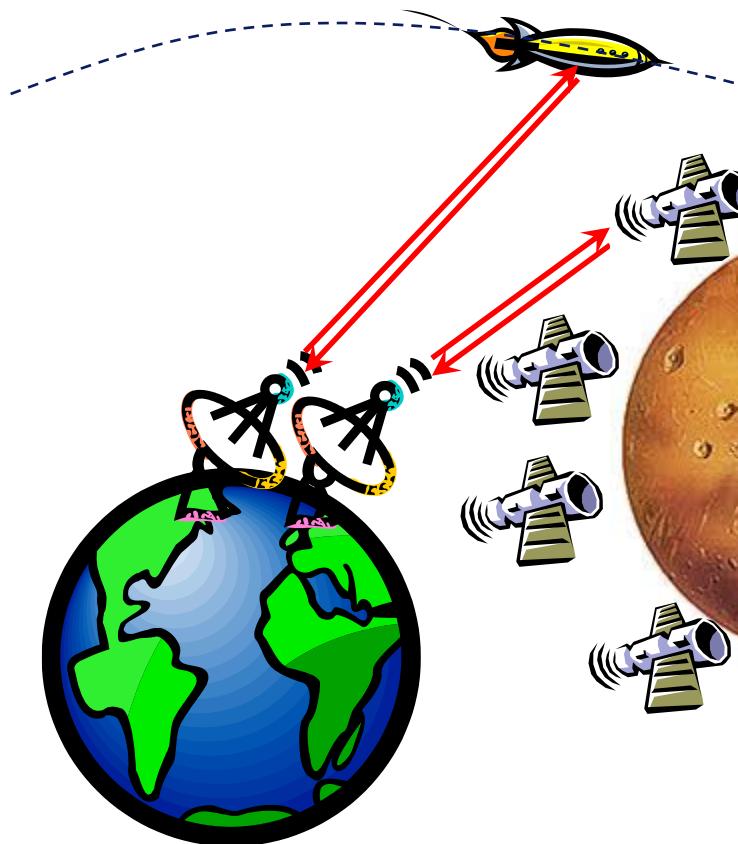


Wikicommons

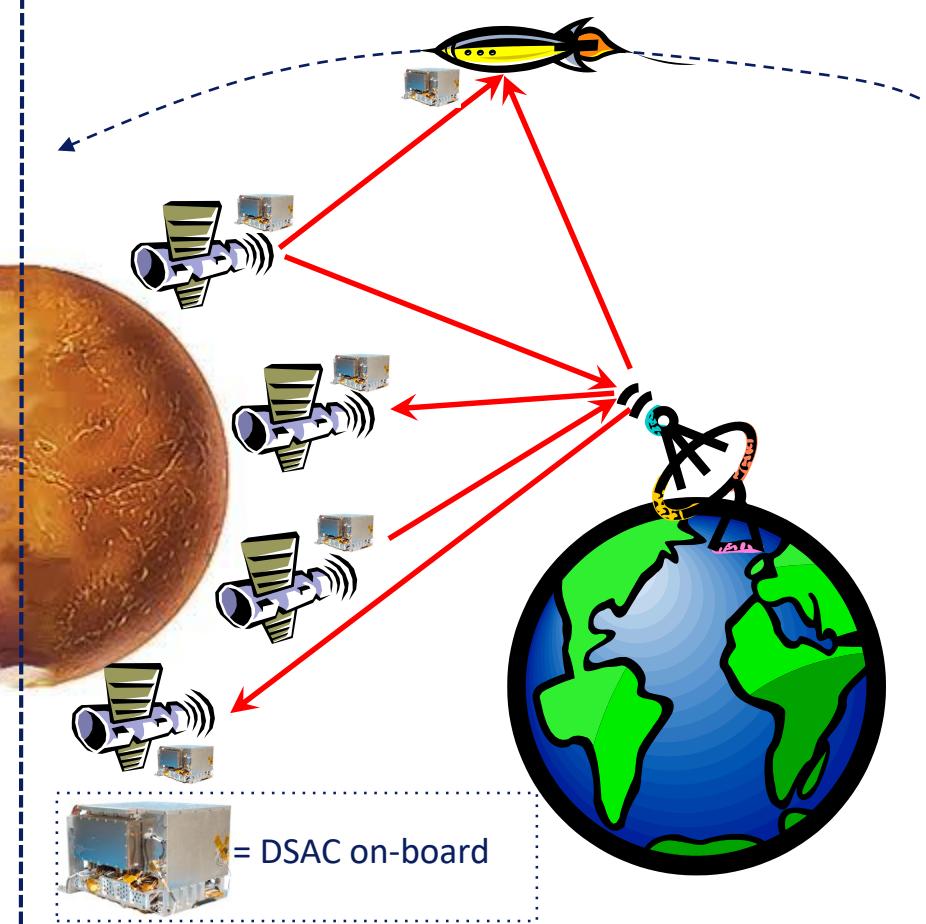
Microwave atomic clock applications: Deep space navigation

Enables Multiple Space Craft Per Aperture Tracking at Mars

Today's 2-Way Radio Navigation



Tomorrow's 1-Way Radio Navigation

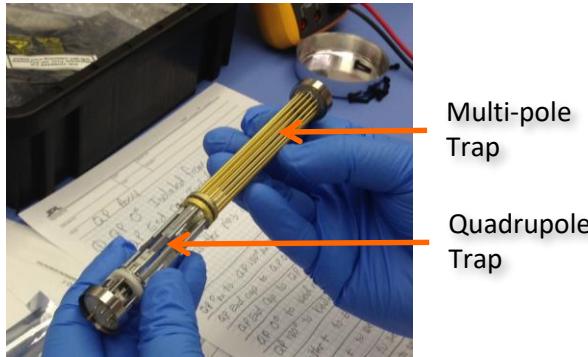


= DSAC on-board

Microwave atomic clock applications: Deep space navigation

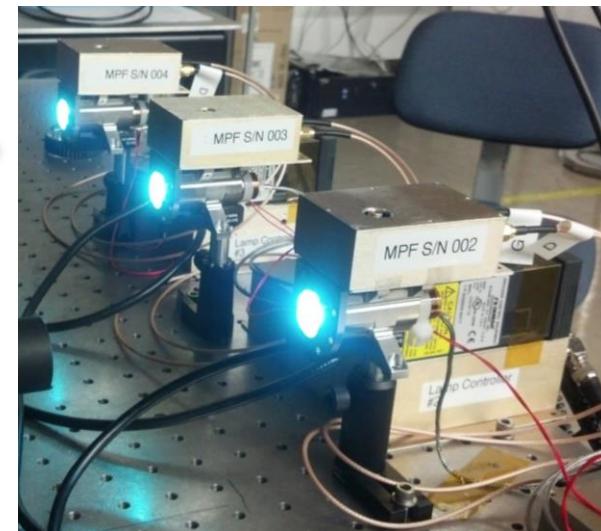
NASA's DSAC Technology Demonstration Mission

DSAC Demonstration Unit



Titanium Vacuum Tube

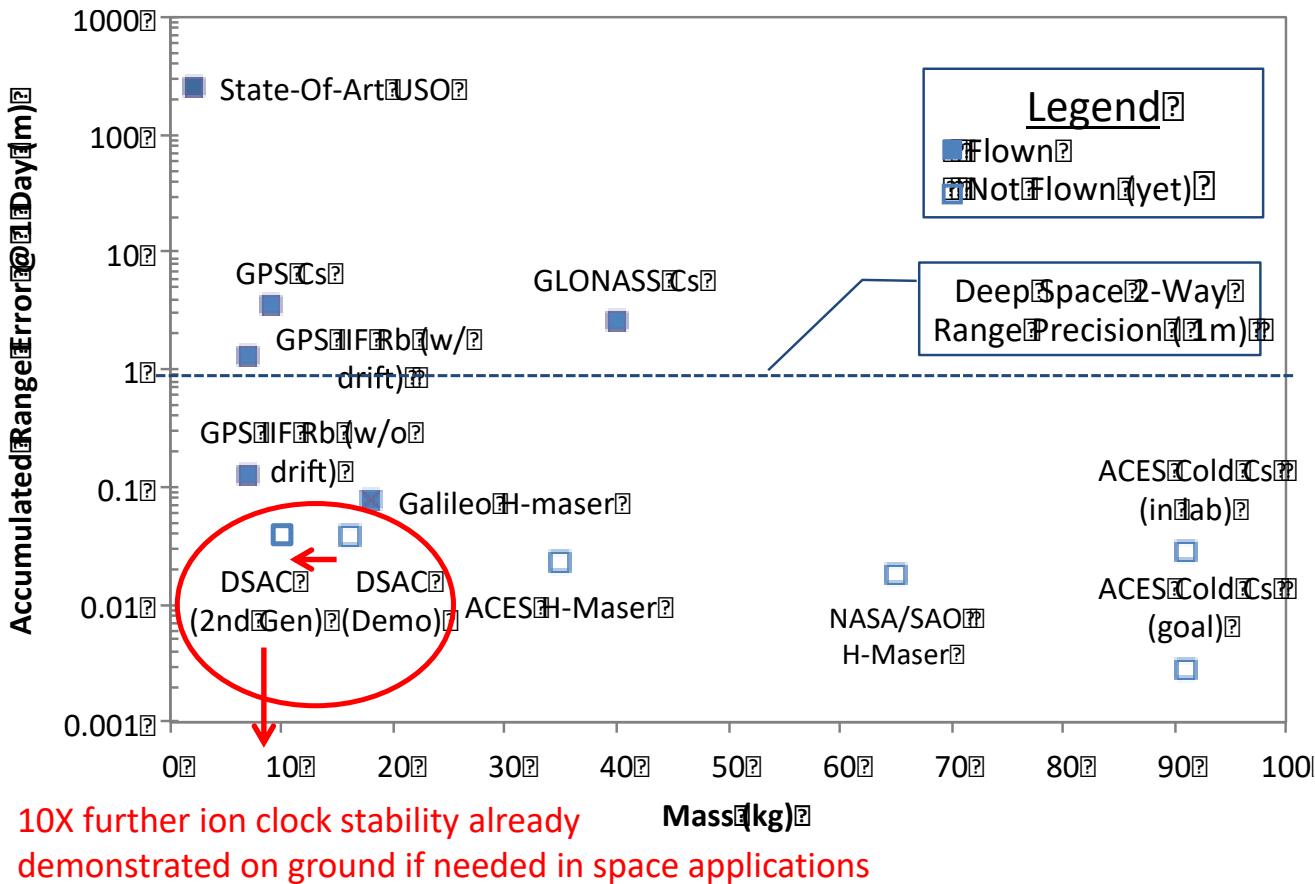
Mercury UV Lamp Testing



Develop advanced prototype ('Demo Unit') mercury-ion atomic clock for navigation/science in deep space and Earth

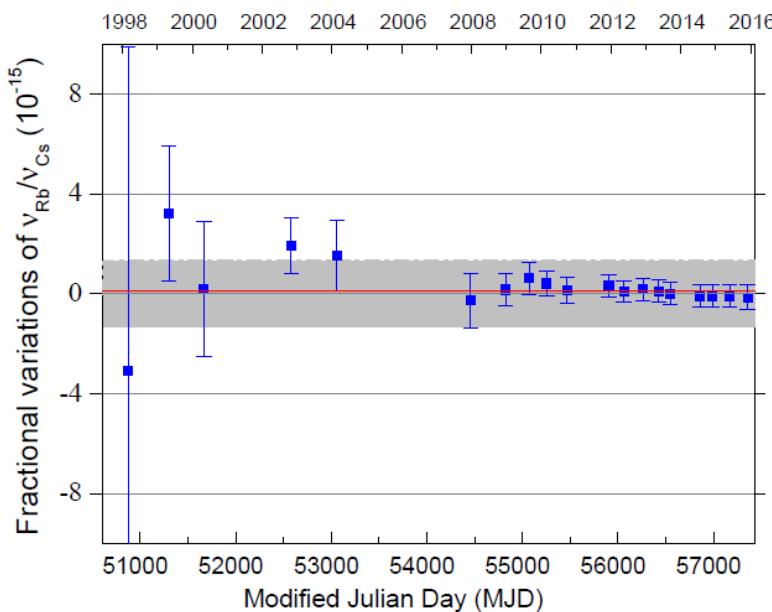
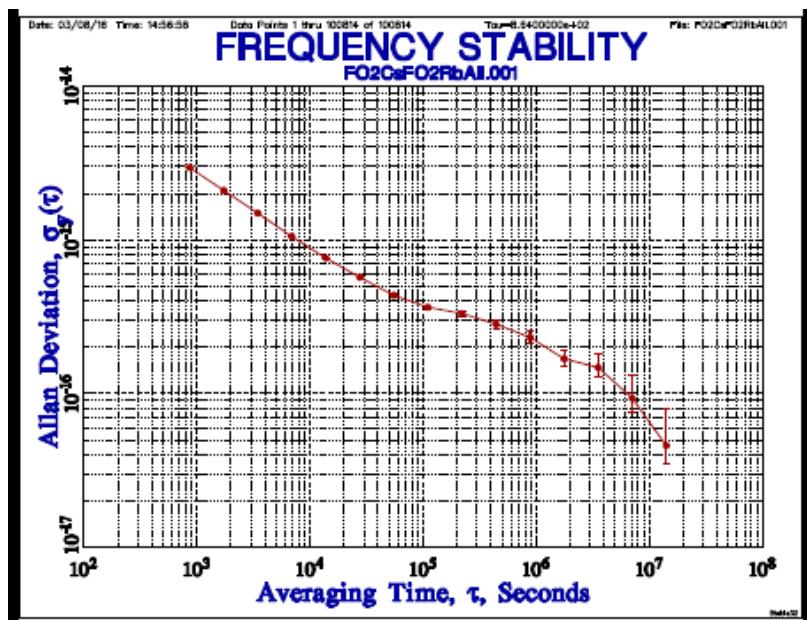
- Perform year-long demonstration in space beginning mid-2016 – advancing the technology to TRL 7
- Focus on maturing the new technology – ion trap and optical systems – other system components (i.e. payload controllers, USO, GPS) size, weight, power (SWaP) dependent on resources/schedule
- Identify pathways to 'spin' the design of a future operational unit (TRL 7 → 9) to be smaller, more power efficient – facilitated by a detailed report written for the next DSAC manager/engineers

DSAC Demonstration Summary & Future



Fundamental Physics with Rb/Cs fountains (SYRTE)

- 16 years of ^{87}Rb ground state hyperfine frequency measurements against Cs : FO2-Rb against FO1 or FOM, and since 2009 against FO2-Cs operated simultaneously.
- Feb. to Aug. 2012 measurement
 $6\,834\,682\,610.904\,312\,(3)\,\text{Hz} \,(\pm 4.4 \times 10^{-16})$
 ⇒ recommended value of Rb hf frequency

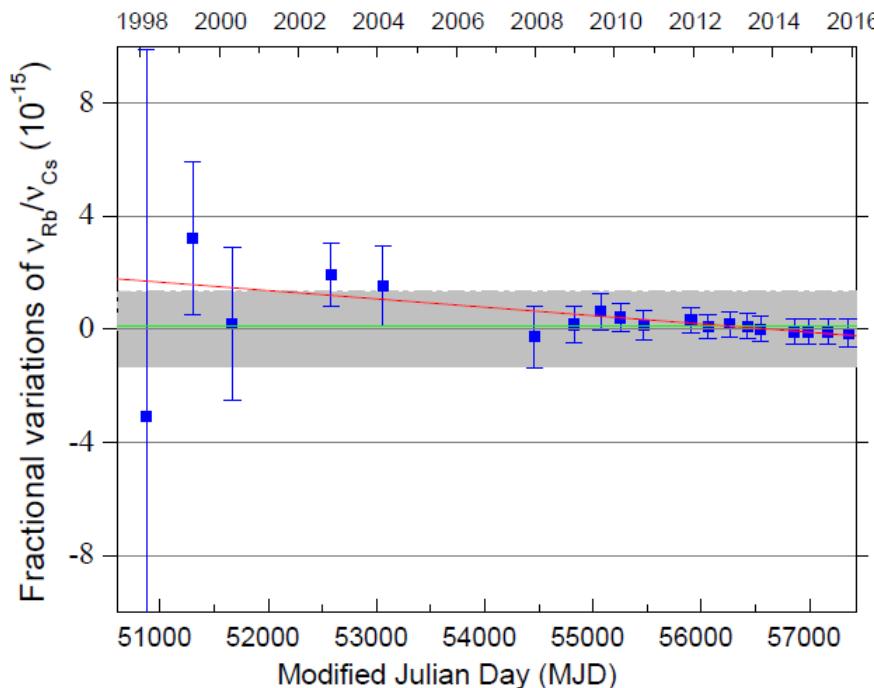


Phys. Rev. Lett. 109, 080801 (2012)

FO2Cs – FO2Rb long term comparison
(Dec. 2009 – Feb. 2016)

average difference 1.1×10^{-16}
statistical unc. down to 4.8×10^{-17}

Rb/Cs: search for time variation in fundamental constants



Phys. Rev. Lett. 109, 080801 (2012)

Weighted least-squares fit to a line

$$\frac{d}{dt} \ln\left(\frac{\nu_{Rb}}{\nu_{Cs}}\right) = (-10.7 \pm 4.9) \times 10^{-17} \text{ yr}^{-1}$$

⇒ limit on a potential variation of fundamental constants :

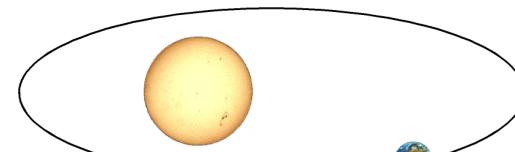
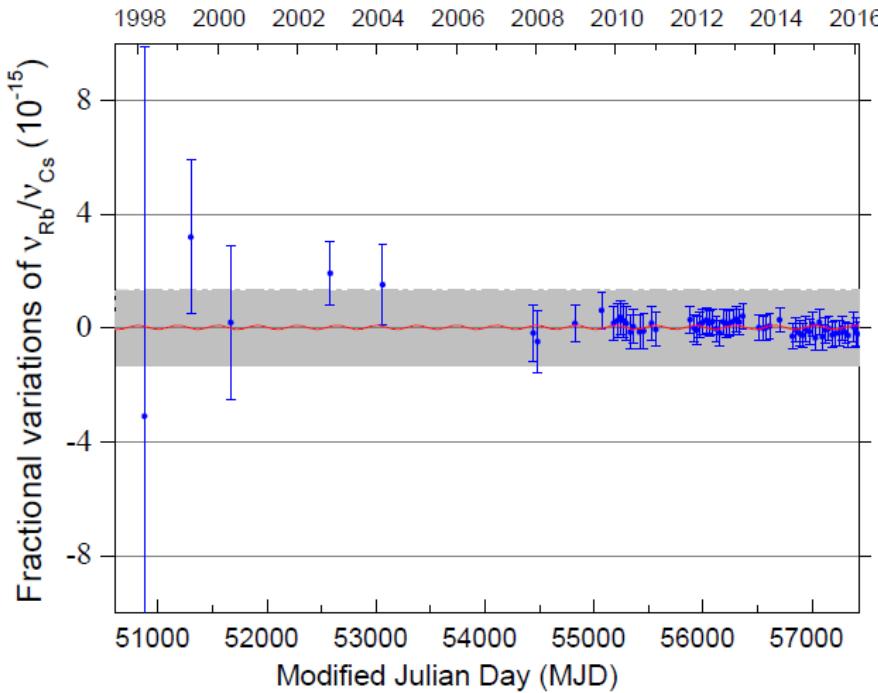
With QED calculations: *J. Prestage, et al., PRL (1995), V. Dzuba, et al., PRA (1999)*

$$\frac{d}{dt} \ln\left(\frac{g_{Rb}}{g_{Cs}} \alpha^{-0.49}\right) = (-10.7 \pm 4.9) \times 10^{-17} \text{ yr}^{-1}$$

With QCD calculations: *T.H. Dinh, et al., PRA79 (2009)*

$$\frac{d}{dt} \ln[\alpha^{-0.49} (m_q / \Lambda_{QCD})^{-0.021}] = (-10.7 \pm 4.9) \times 10^{-17} \text{ yr}^{-1}$$

Rb/Cs: search for annual variations



$$\frac{\Delta U(t)}{c^2} \simeq -\frac{GM_\odot}{c^2 a} \epsilon \cos[\Omega(t - t_{perihelion})]$$

$$d \ln\left(\frac{v_{Rb}}{v_{Cs}}\right) = C + (0.8 \pm 0.9) \times 10^{-16} \cos[\Omega_\oplus(t - t_{perihelion})]$$

$$c^2 \frac{d}{dU} \ln\left(\frac{v_{Rb}}{v_{Cs}}\right) = (-4.7 \pm 5.3) \times 10^{-7}$$

► Differential redshift test

$$d\nu/\nu = (1 + \beta)dU/c^2$$

$$\beta(^{87}Rb) - \beta(^{133}Cs) = (-4.7 \pm 5.3) \times 10^{-7}$$

► Variation of constants with gravity

$$c^2 \frac{d}{dU} \ln\left(\frac{g_{Rb}}{g_{Cs}} \alpha^{-0.49}\right) = (-4.7 \pm 5.3) \times 10^{-7}$$

$$\frac{d}{dt} \ln(\alpha^{-0.49} (m_q / \Lambda_{QCD})^{-0.021}) = (-4.7 \pm 5.3) \times 10^{-17} \text{ yr}^{-1}$$

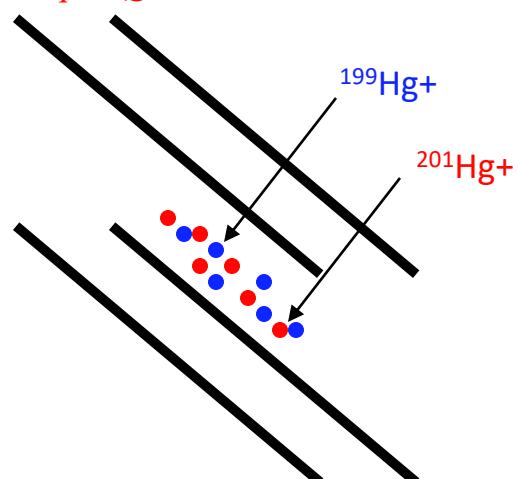
Fundamental Physics with Ion Clocks: $^{201}\text{Hg}^+/\text{Hg}^+$ Dual Isotope Clock

- HF clocks: depend on α , μ via $A \propto (m_e e^4 / \hbar^2) [\alpha^2 F_{\text{rel}}(Z\alpha)] (\mu m_e / m_p)$
 - some ambiguity
- Direct optical clock comparisons depend only on α
- $\mu \propto m_q / \Lambda_{QCD}$ *
- $B_{201} \approx -B_{199}$ **:

$$\frac{\eta}{\eta t} \ln \frac{f_{201}}{f_{199}} = [B_{201} - B_{199}] \frac{\eta}{\eta t} \ln \frac{\frac{m_q}{\Lambda_{QCD}}}{\frac{m_q}{\Lambda_{QCD}}} \div$$

- $B_{201} - B_{199} \approx 0.2$ - BIG!
- Would provide a stand-alone independent limit on m_q / Λ_{QCD} variation

Dual isotope clock will reduce systematic sensitivity in difference measurement



*V.V. Flambaum and A.F. Tedesco, Phys. Rev. C 73, 055501 (2006)

**S.N. Lea, to be published in the Eur. Phys. J ST.

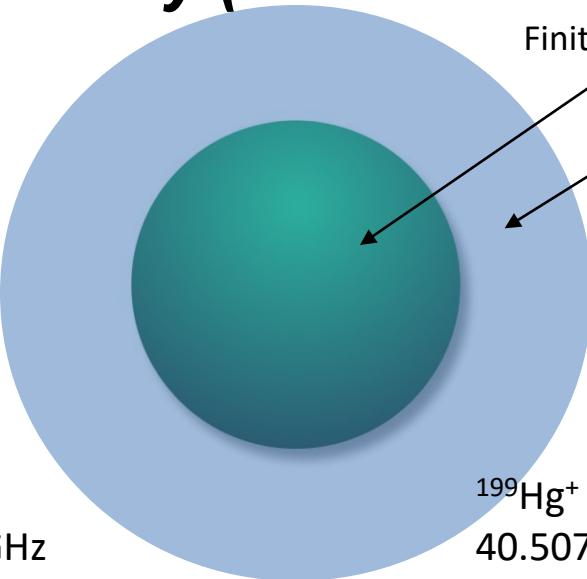
Fundamental Physics with Ion Clocks: Hyperfine Anomaly (Bohr-Weisskopf Effect*)



E.A. Burt, JPL

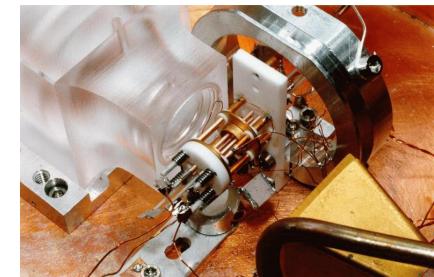
$^{201}\text{Hg}^+$ HF clock:
29.9543658213(17) GHz

(E.A. Burt, et al., PRA 79, 062506 (2009))



Finite size nucleus

S electron:
Finite probability to be at nucleus



Courtesy J. Bergquist, NIST

$^{199}\text{Hg}^+$ HF clock:
40.50734799684159(41) GHz

(D.J. Berkeland, et al., PRL 80, 2089 (1998))

Point nucleus:

$$\frac{\Delta f_1}{\Delta f_2} = \left(\frac{\mu_{I1}/I_1}{\mu_{I2}/I_2} \right) \frac{F_1}{F_2}$$

Finite nucleus:

$$\frac{\Delta f_1}{\Delta f_2} = (1 + \Delta) \left(\frac{\mu_{I1}/I_1}{\mu_{I2}/I_2} \right) \frac{F_1}{F_2}$$

HF anomaly

*A. Bohr and V.F. Weisskopf, PR 77, 94 (1950)

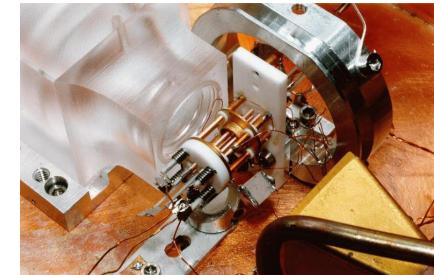
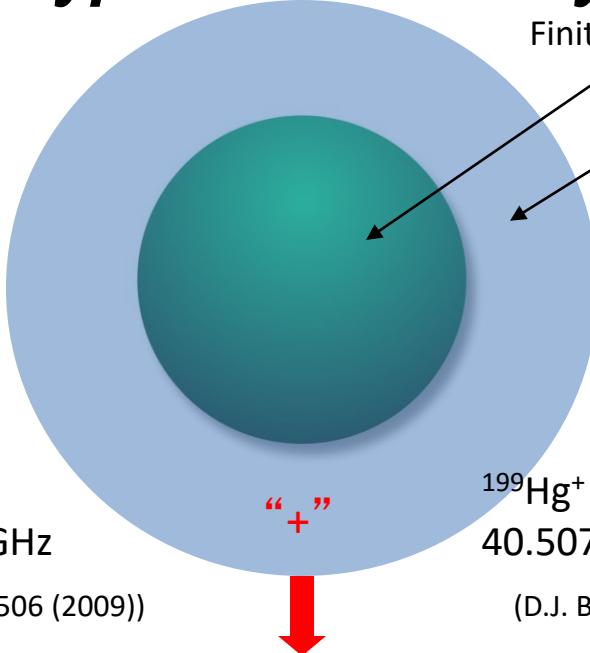
Fundamental Physics: The Hyperfine Anomaly



E.A. Burt, JPL

$^{201}\text{Hg}^+$ HF clock:
29.9543658213(17) GHz

(E.A. Burt, et al., PRA 79, 062506 (2009))



Courtesy J. Bergquist, NIST

$^{199}\text{Hg}^+$ HF clock:
40.50734799684159(41) GHz

(D.J. Berkeland, et al., PRL 80, 2089 (1998))

$$\frac{\Delta f_1}{\Delta f_2} = (1 + \Delta) \left(\frac{\mu_{I1}/I_1}{\mu_{I2}/I_2} \right) \frac{F_1}{F_2} \quad \frac{f_{201}}{f_{199}} = -0.739479805577(3)$$

$$\Delta(S_{1/2}, {}^{199}\text{Hg}^+, {}^{201}\text{Hg}^+) = -0.0016257(5)$$

E.A. Burt, et al., PRA 79, 062506 (2009)

Previous values Hg: -0.001627(19), (Reimann and McDermott, PRC 7, 2065 (1973))
 Hg⁺: -.0034 to +0.0056 (Grandinetti, et al., (1986))

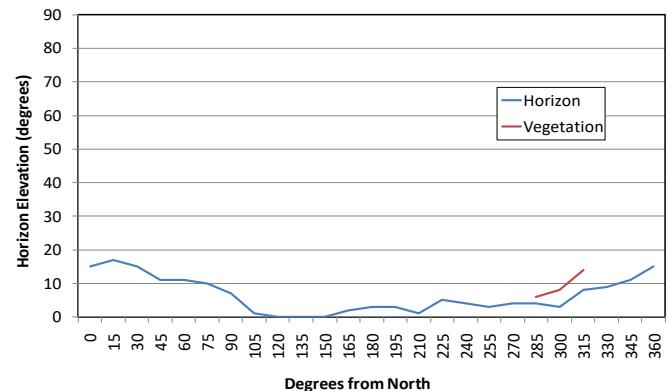
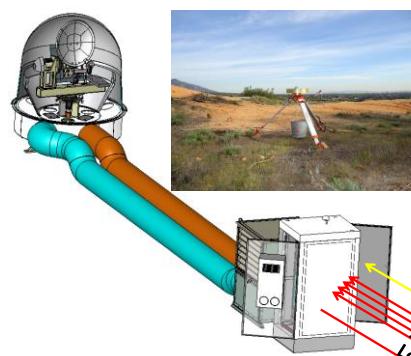
- Value now limited by knowledge of μ_l
- Agrees with neutral value: valence screening has minimal effect

Fundamental Physics and ACES



ISS

ACES ground terminal

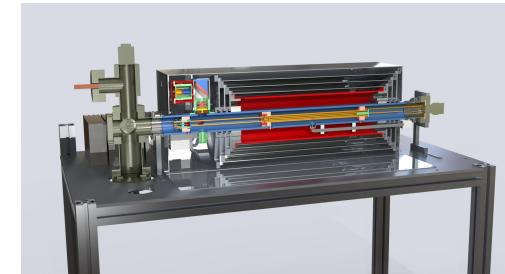


Degrees from North

FSTL:



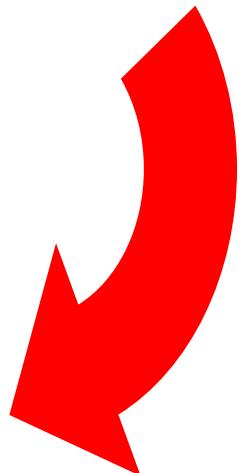
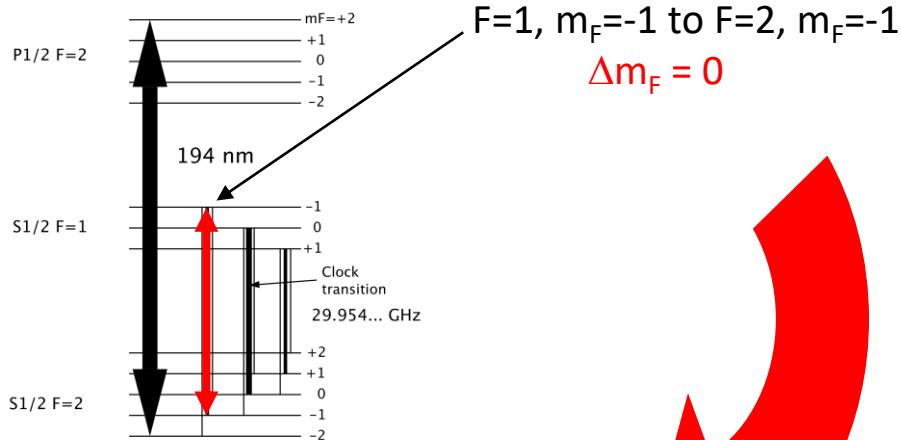
FSTL1 reference:



- **Timing Accuracy in Space**
- **Improved Gravitation Red Shift Measurement**

Microwave Clock Applications: Magnetometry Doppler-Free Field-Sensitive Spectroscopy

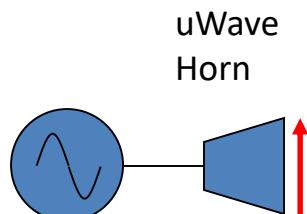
- would like to measure the field AT the ions



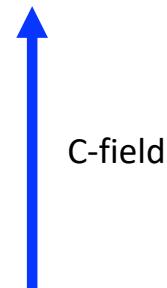
**Lamb-Dicke
Confinement:**

$$\lambda = 1 \text{ cm}$$

$$r_0 < 1 \text{ mm}$$

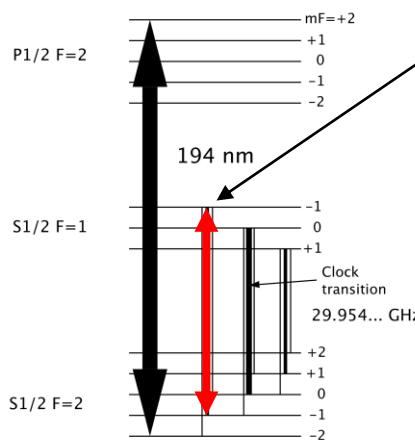


29.954... GHz

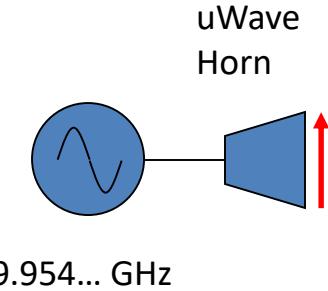
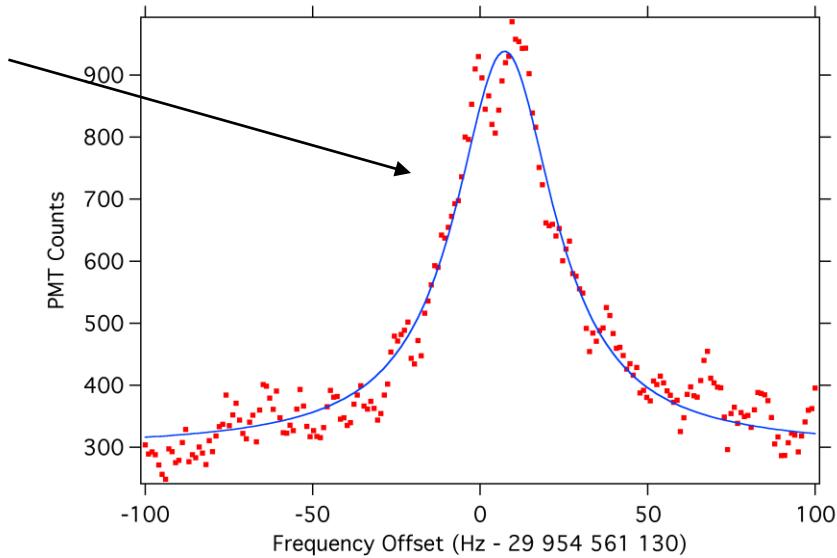


Doppler-Free Field-Sensitive Spectroscopy

- simultaneously operated dual isotope ion clock:
clock isotope + magnetometer isotope



$F=1, m_F=-1$ to $F=2, m_F=-1$
 $\Delta m_F = 0$



uWave
Horn
 $C\text{-field}$

$$f_{-1,-1} = 29\ 954\ 561\ 137(30) \text{ Hz}$$

$$B_0 = 139.341(42) \text{ mG}$$

$$\Delta f = +195 \text{ kHz}$$

E.A. Burt, et al., PRA 79, 062506 (2009)

Residual broadening due to C-field current source instability

- space applications
- $^{201}\text{Hg}^+$ magnetometer for $^{199}\text{Hg}^+$

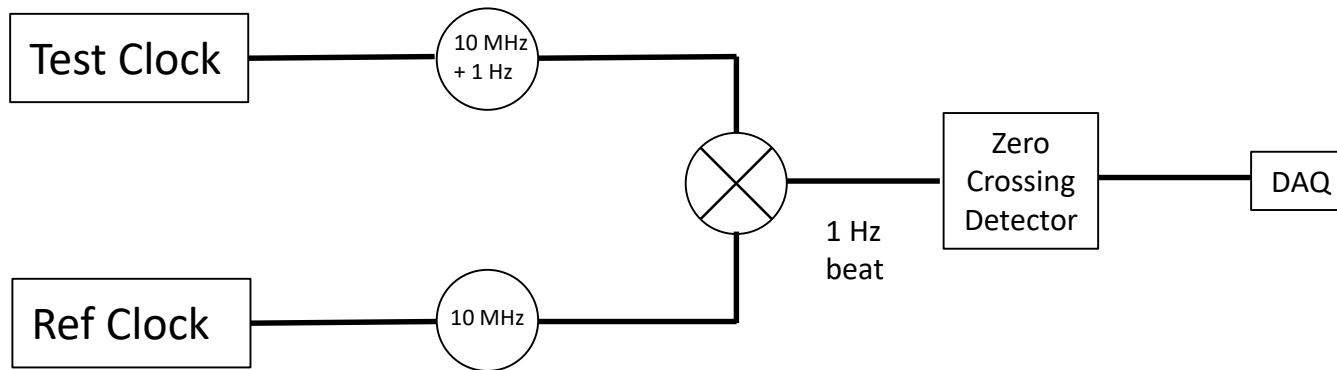
Microwave Atomic Clocks Summary

CLOCK	SHORT-TERM (at 1 s)	LONG-TERM	DRIFT (per day)	SPACE VERSION BUILT	SPACE VERSION FLOWN
CSAC	8e-11		4e-12	Yes?	Yes??
Cs beam	4e-12 to 2e-11	< 1e-14		Yes	Yes
Rb gas cell	< 5e-12		6e-13	Yes	Yes
H-maser	1e-13	< 1e-15	2e-15 to 2e-16	Yes	Yes
Fountain	1e-14 to 2e-13	< 1e-17	None	Yes	No
Laser-cooled ion	4e-14 to 3e-13		None	No	No
Room-temp ion	2e-14 to 3e-13	< 1e-16	< 3e-17	Yes	No

Backup Slides

How Do We Compare Clocks

SAME LAB: 1 Hz offset method



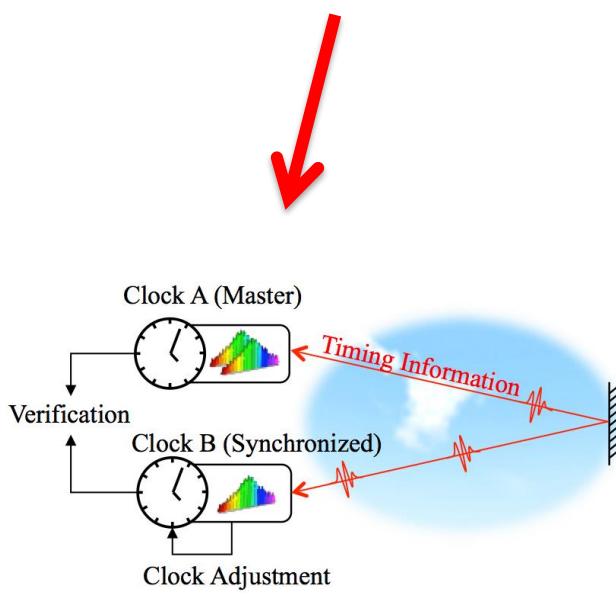
Example:

- 1e-13 change is $\sim 1 \mu\text{Hz}$ on 10 MHz
- $\Rightarrow 1\text{e-}13 \text{ s}$ change in phase in one cycle
- On 1 Hz beat note, this is integrated for 1 s to give a 1 μs phase change on the 1 Hz beat
- 1e-13 s is very hard to detect, 1 μs is readily detected.

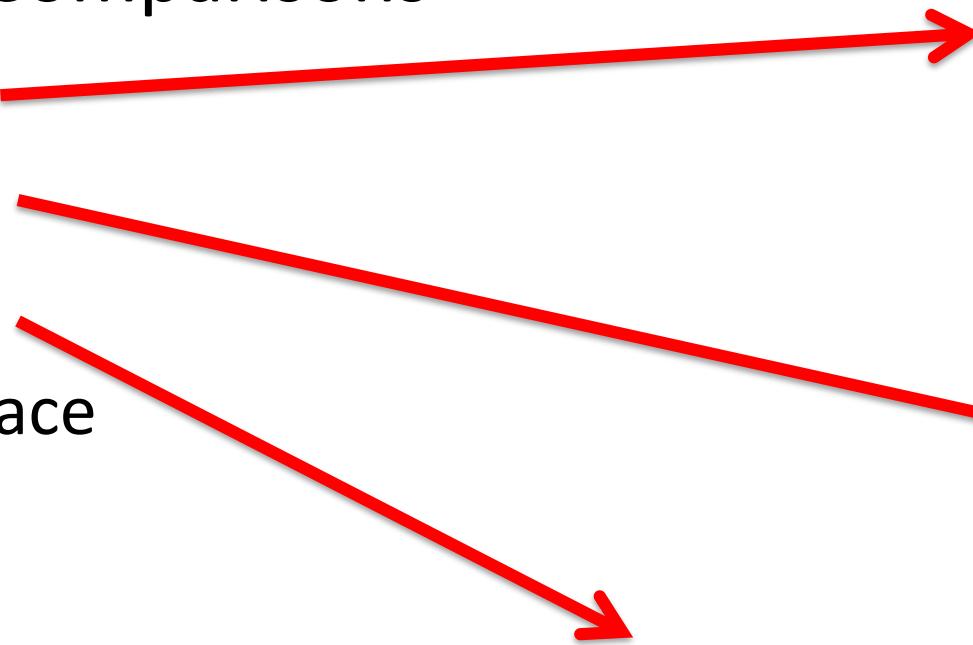
How Do We Compare Clocks

- Remote Comparisons

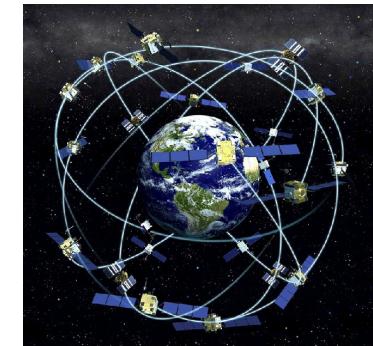
- GPS
- TWSTT
- Fiber
- Free space



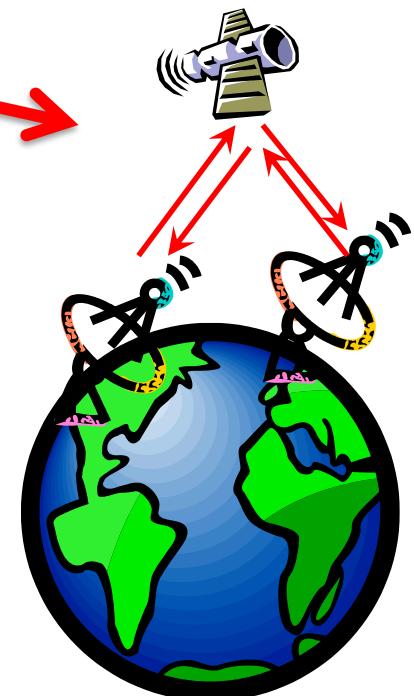
Courtesy N. Newbury, L. Sinclair, NIST



Wikicommons



Wikicommons



Wikicommons

World Time Standards

“Bureau International des Poids et Mesures” (BIPM)

- UTC
- UTC(x)
 - USNO, NIST, OP, PTB, NPL, etc...
- TAI: Atomic Time
- TT(BIPM): Primary Standards
- Other...

Selected Textbook References

(see specific slides for journal references)

Atomic Physics

- “Elementary Atomic Structure”, 2nd Edition, G.K. Woodgate, Oxford (1986)
- “Atomic Physics”, C.J. Foot, Oxford (2005)

Trapping and Cooling of Atoms

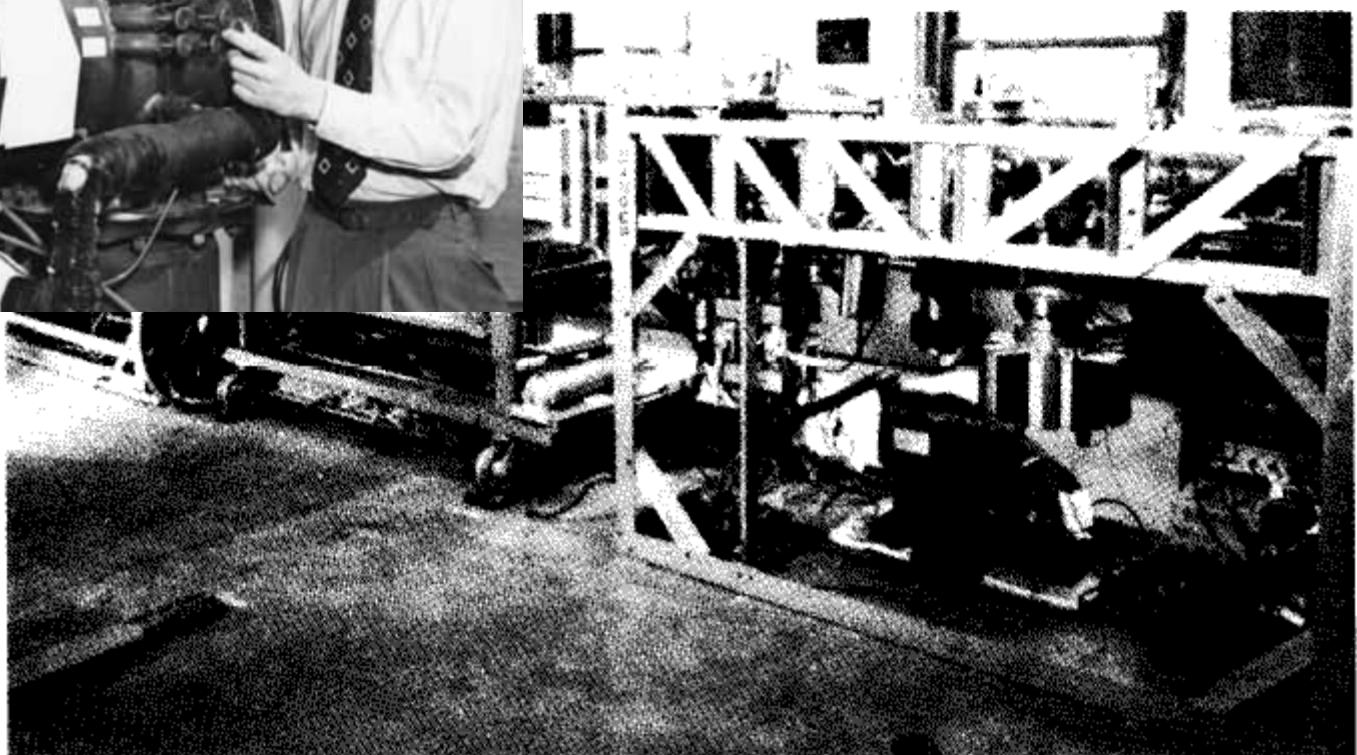
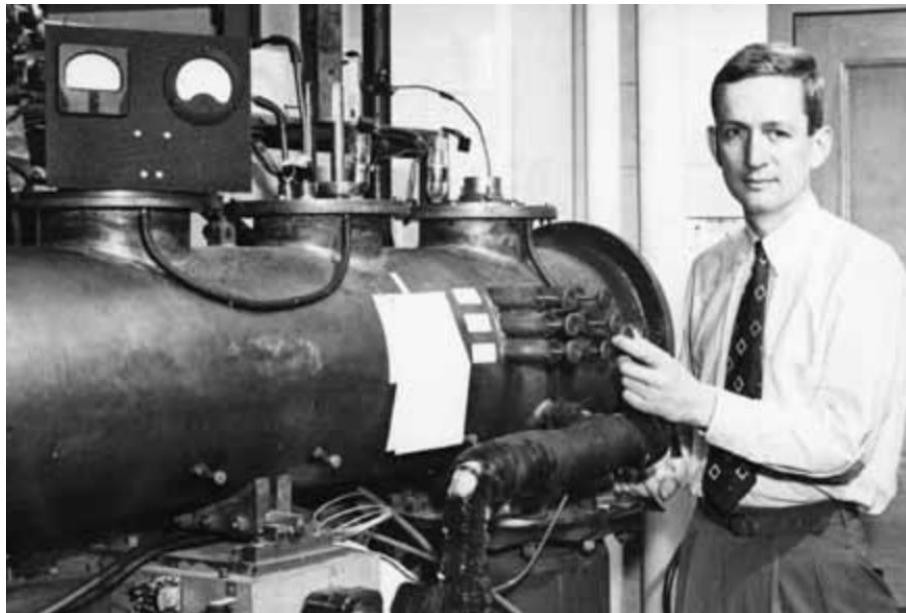
- “Laser Cooling and Trapping”, H.J. Metcalf and P. van der Straten, Springer (1999)

Atomic Clocks

- “The Quantum Physics of Atomic Frequency Standards”, J. Vanier and C. Audoin, CRC Press
- “The Quantum Physics of Atomic Frequency Standards – Recent Developments”, J. Vanier and C. Tomescu, CRC Press (2016)

Cesium Beam Tube

Ramsey's Lab - 1949



©Oxford University Press
N. Ramsey, "Molecular Beams," 1956

Cesium Beam Tube



1975 National Bureau of Standards
U.S. Gov't not subject to copyright

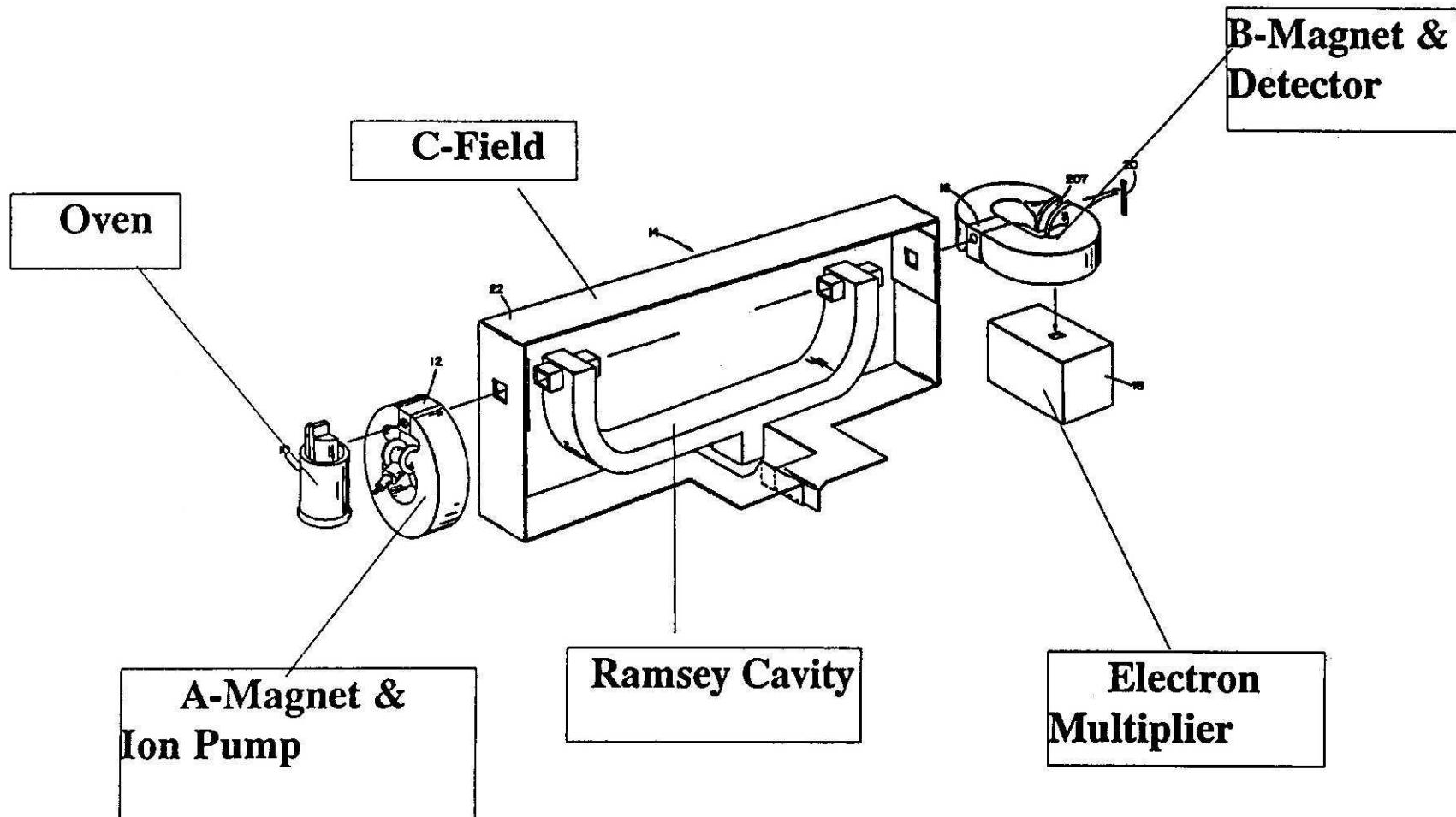
NBS-6 circa 1975



©Physikalisch-Technische Bundesanstalt
www.flickr.com

PTB CS1 (1965 - present)

Cesium Beam Tube Construction

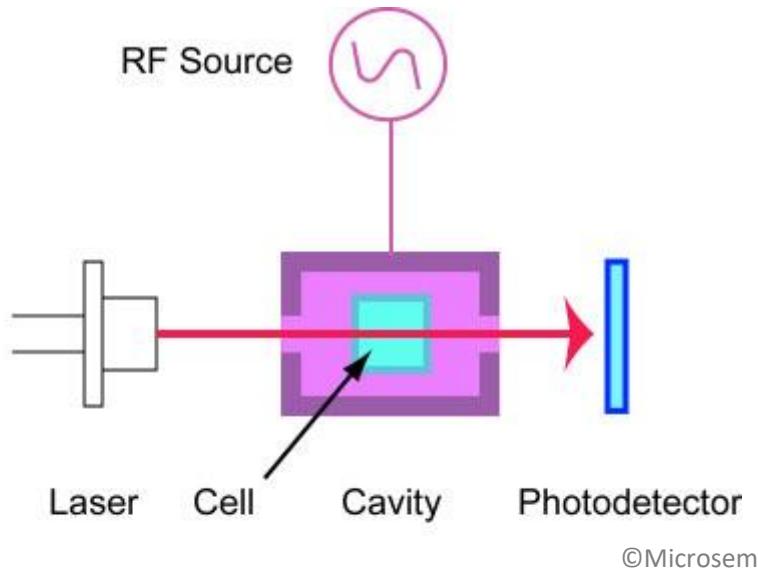


Source: U.S. Patent # 3,967,115

Microwave Atomic Clock Examples: Chip Scale Atomic Clocks

Microwave atomic clock examples: Chip-Scale Atomic Clock (CSAC)

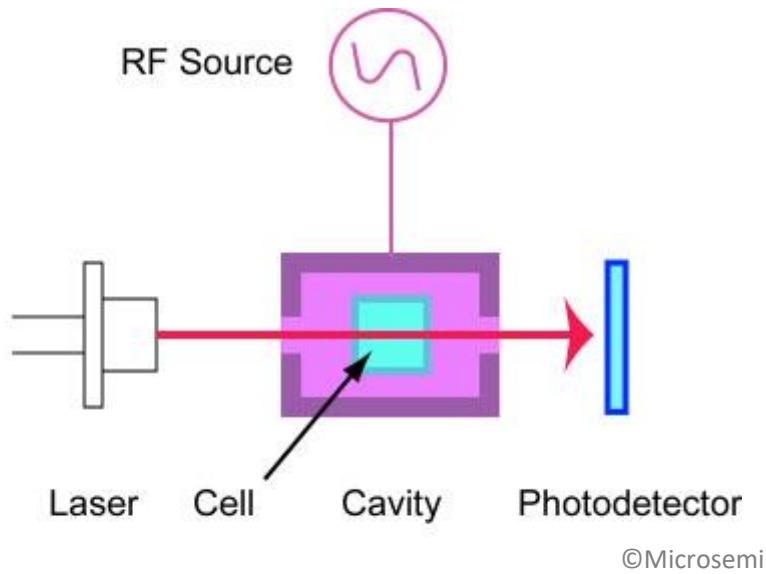
Cavity approach: use laser + microwave cavity



Requires finite size Resonant Cavity

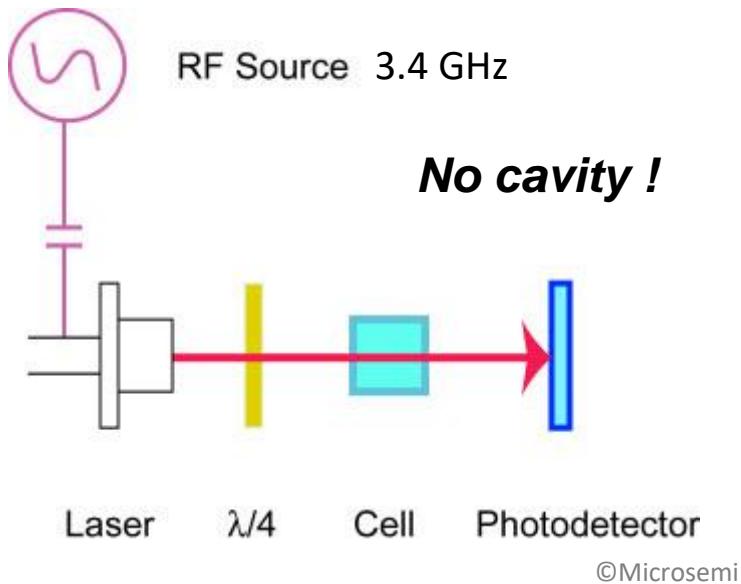
Microwave atomic clock examples: Chip-Scale Atomic Clock (CSAC)

Cavity approach: use laser + microwave cavity

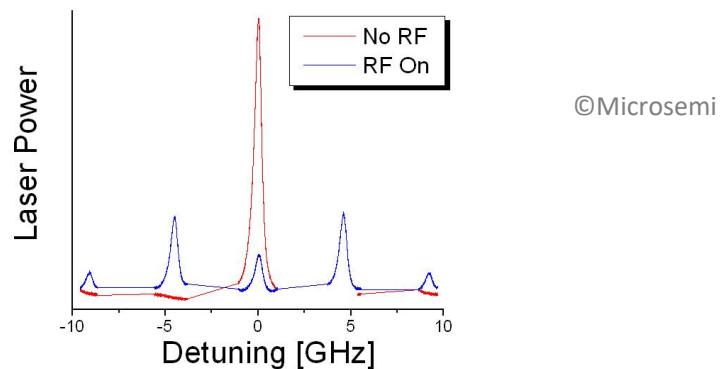


Requires Resonant Cavity

CSAC approach: use laser + CPT

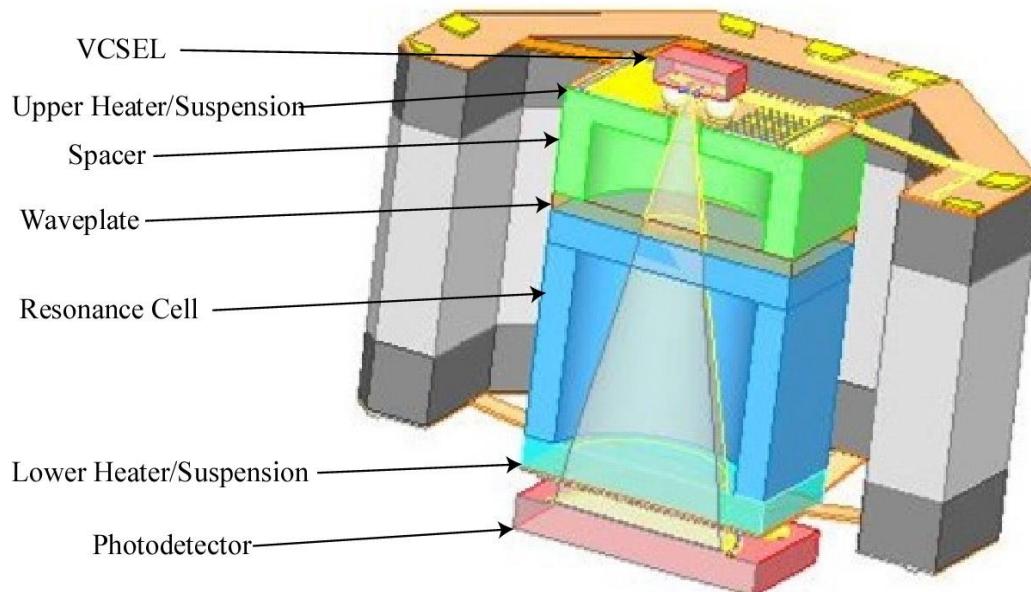


High-Bandwidth VCSEL is Enabling Technology



Coherent population trapping (CPT): when frequency difference of sidebands matches HF clock transition, get a dark state and transmission increases.

CSAC: A 10 mW Physics Package



©Charles Stark Draper Laboratory

- ⌚ Tensioned polyimide suspension
- ⌚ Microfabricated Silicon vapor cell
- ⌚ Low-power Vertical-Cavity Surface Emitting Laser (VCSEL)
- ⌚ Vacuum-packaged to eliminate convection/conduction
- ⌚ Overall Thermal Resistance $7000^{\circ}\text{C}/\text{W}$

M. Mescher, et. Al., "An Ultra-Low-Power Physics Package for a Chip-Scale Atomic Clock," *Proceedings of the 13th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers '05)*, Seoul, Korea, June 5-9, 2005, pp. 311-316.

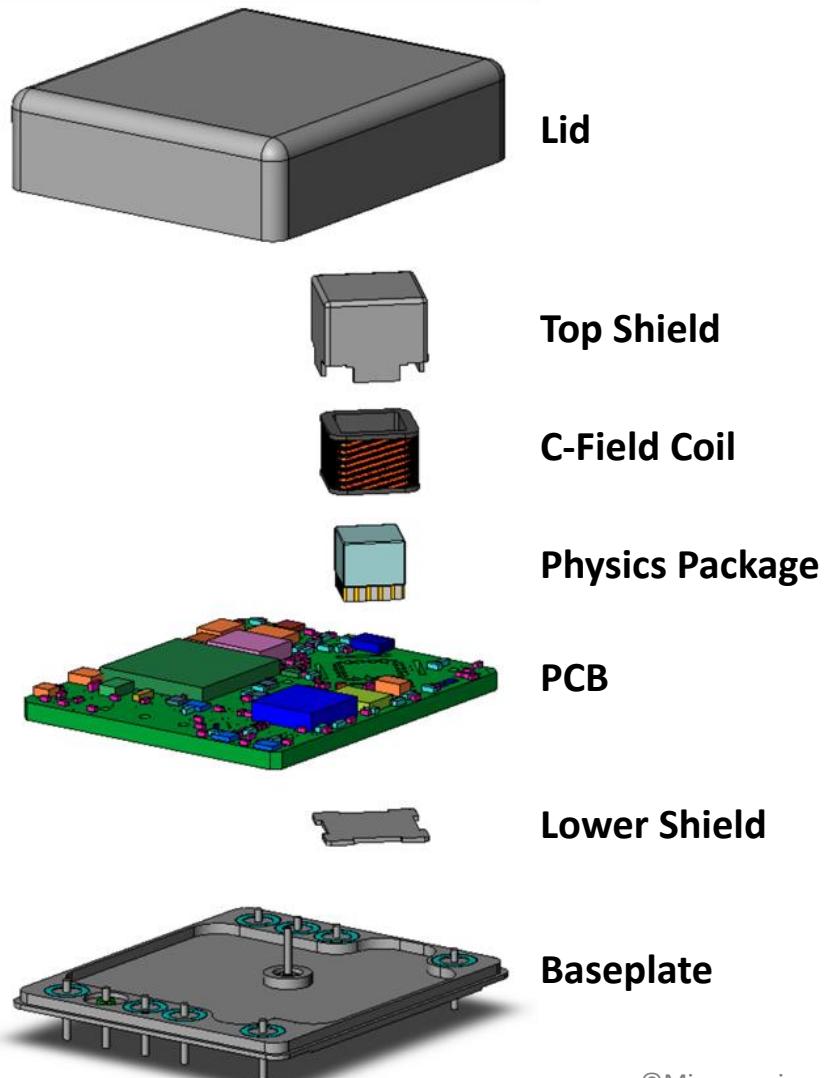
Commercial CSAC: SA.45s



©Microsemi

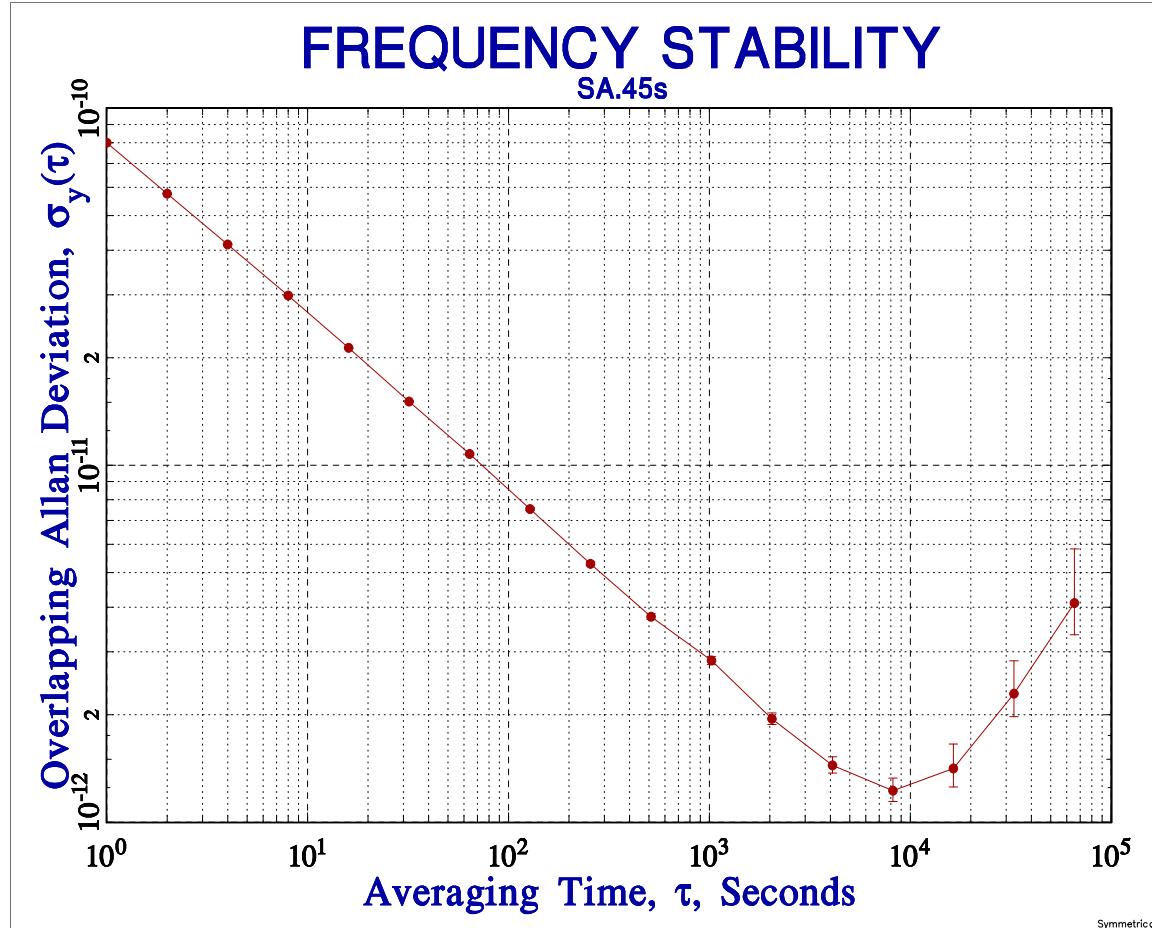


©Microsemi



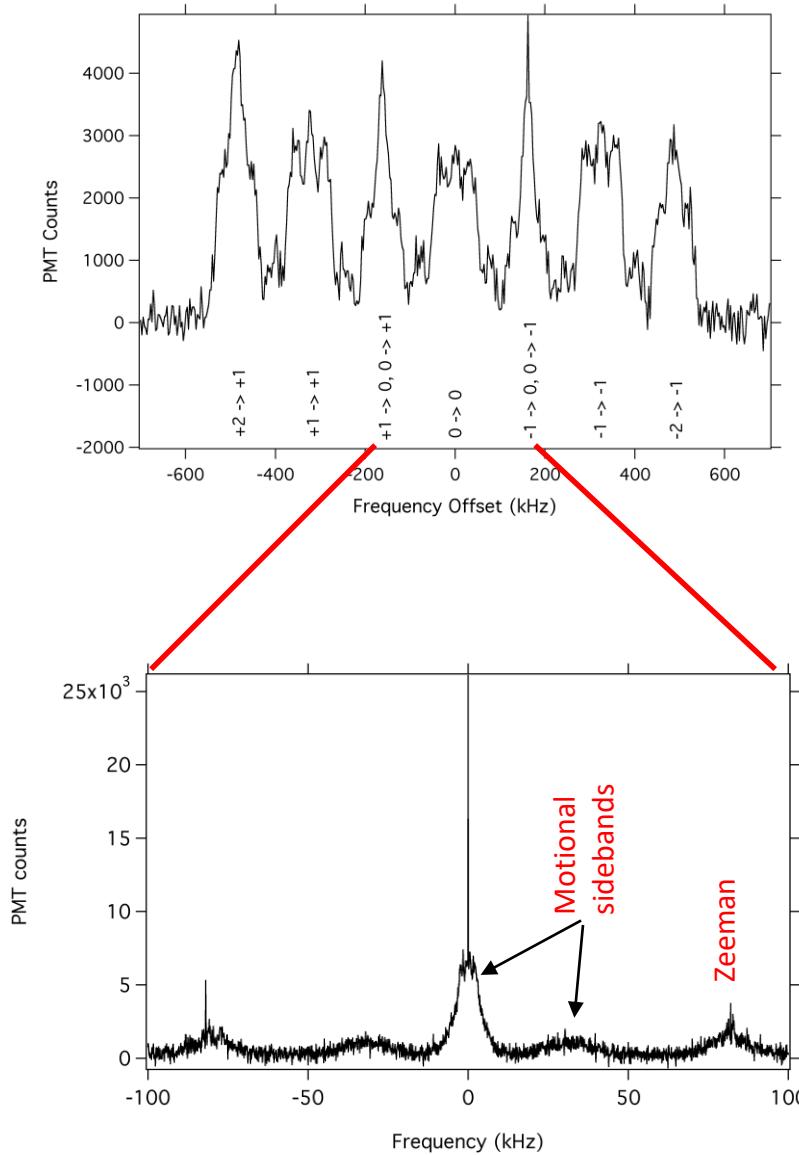
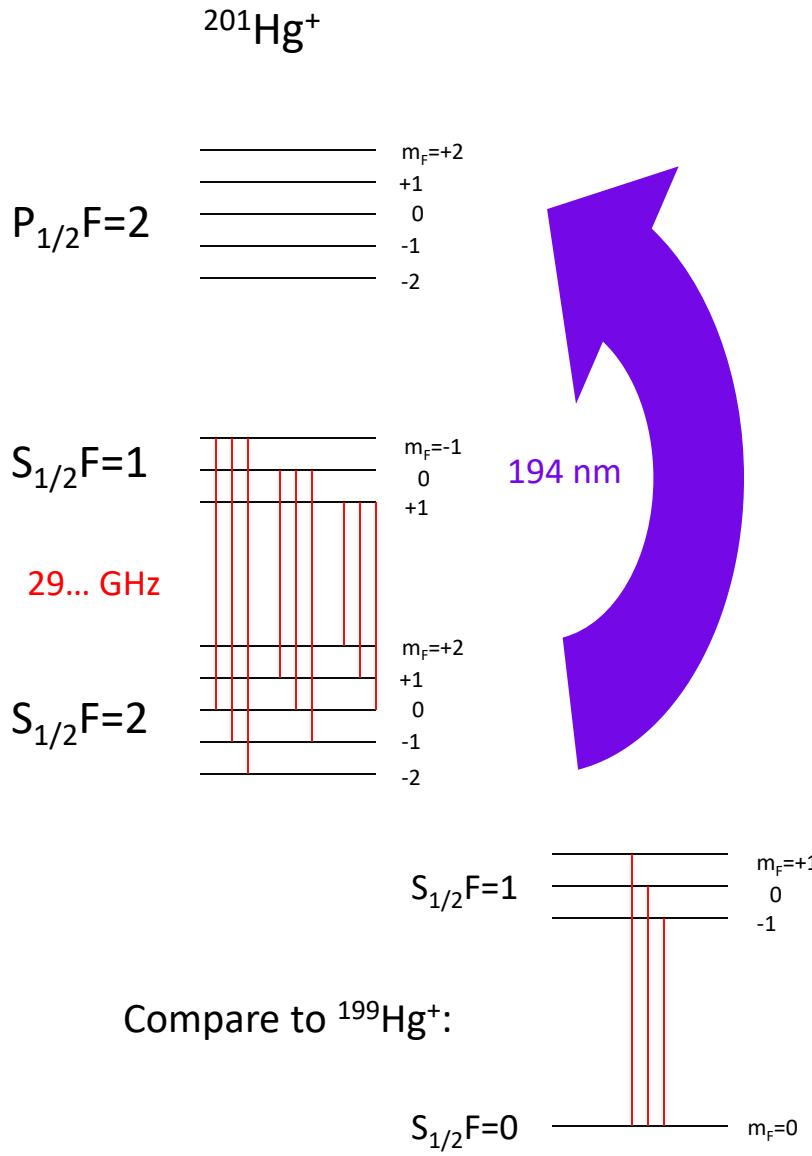
©Microsemi

CSAC SA.45s Performance Summary



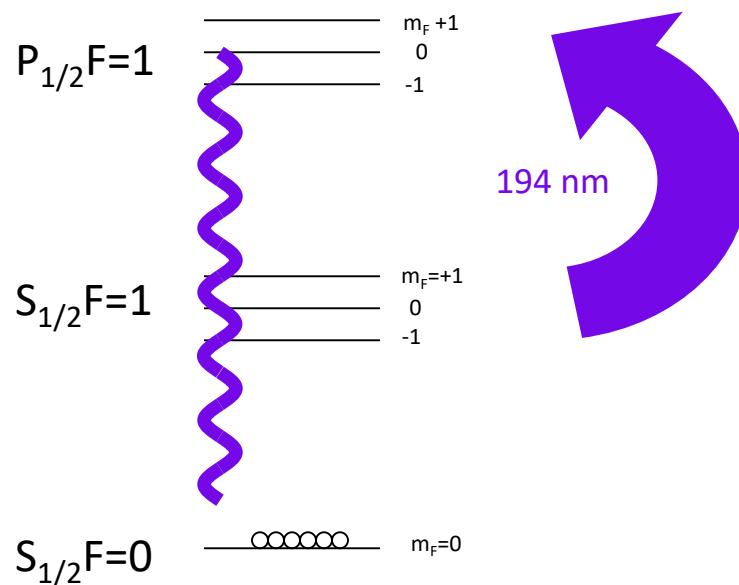
Short term stability: $8e-11/\sqrt{\tau}$
Long term drift: $4e-12/\text{day}$

Mercury Ion Level Structure Revisited: State Preparation Challenges

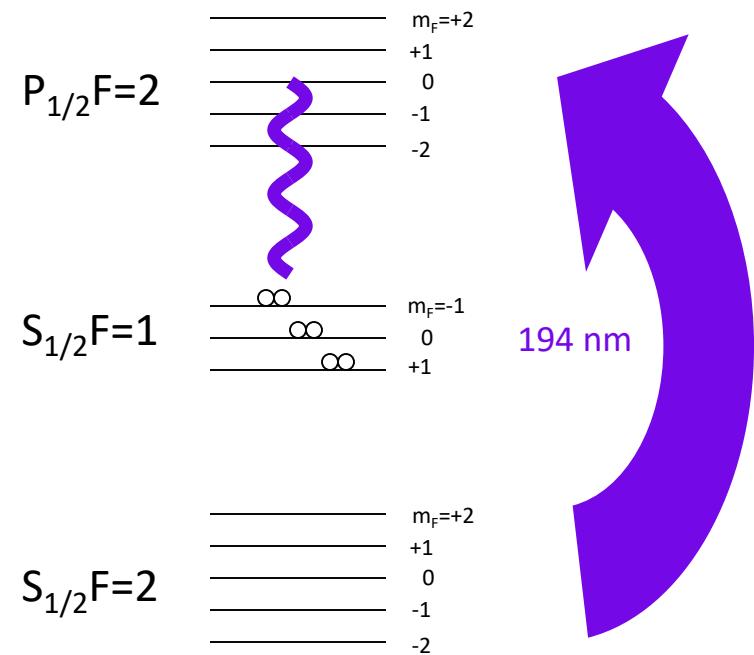


Mercury Ion Level Structure Revisited: State Preparation Challenges

$^{199}\text{Hg}^+$ Optical Pumping

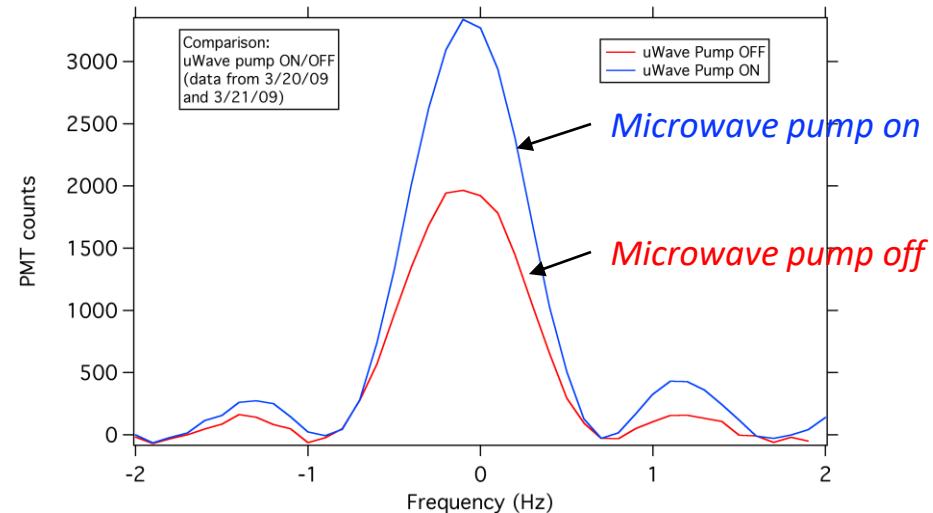
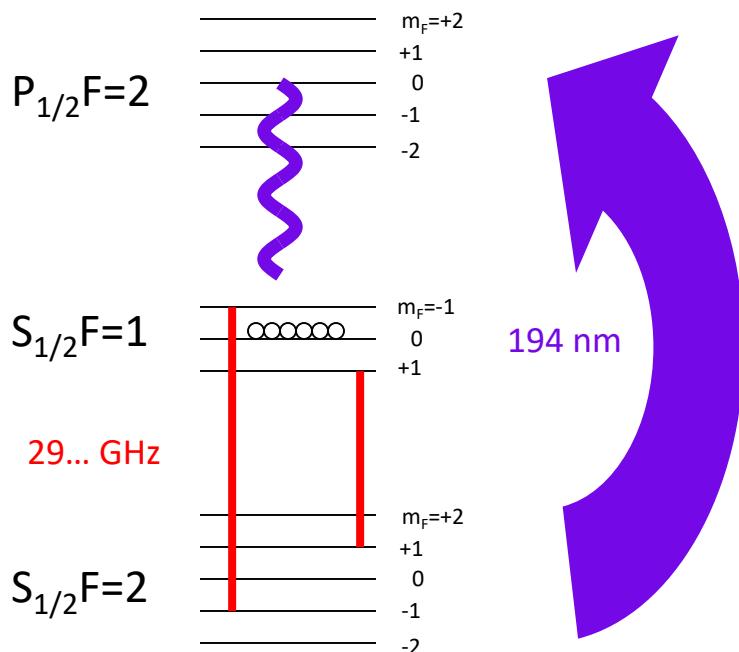


$^{201}\text{Hg}^+$ Optical Pumping



Mercury Ion Level Structure Revisited: State Preparation Challenges

$^{201}\text{Hg}^+$ Optical/Microwave Pumping scheme



Microwave pump:

- $\Delta m=0 \Rightarrow$ polarization same as clock
- inverted level structure $\Rightarrow \Delta m=0$ levels well resolved

How to Interpret the Allan Deviation

Tau Power Law
White phase: -1
White freq: -1/2
Flicker: 0
Random Walk freq: +1/2
Linear drift: +1

